The *NC-4*

This historic airplane, the Navy-Curtiss No. 4 (known as the *NC-4*) completed the first transatlantic flight on May 31, 1919, by flying from Rockaway, Long Island, to Plymouth, England, a journey of 4513 miles on which five stops were made en route. Her wing-spread is 126 ft., and her weight when manned and loaded was 14 tons. Lieutenant Commander Albert Cushing Read of the United States Navy commanded her during the flight. Twenty United States destroyers were stationed at intervals of about 70 miles along the route from Newfoundland to the Azores, the longest leg of the flight (1380 miles)

PRACTICAL PHYSICS

BY

ROBERT ANDREWS MILLIKAN, PH.D., SC.D.
PROFESSOR OF PHYSICS IN THE UNIVERSITY OF CHICAGO

AND

HENRY GORDON GALE, PH.D.
PROFESSOR OF PHYSICS IN THE UNIVERSITY OF CHICAGO

BEING A REVISION OF THE AUTHORS' "A FIRST COURSE IN PHYSICS" DONE IN COLLABORATION WITH

WILLARD R. PYLE, B.S.
HEAD OF THE DEPARTMENT OF PHYSICS, MORRIS HIGH SCHOOL
NEW YORK CITY

GINN AND COMPANY
BOSTON · NEW YORK · CHICAGO · LONDON
ATLANTA · DALLAS · COLUMBUS · SAN FRANCISCO

321.3

The Athenæum Press
GINN AND COMPANY · PRO-
PRIETORS · BOSTON · U.S.A.

PREFACE

The chief aim of this book in all of its editions has been to present *elementary physics in such a way as to stimulate the pupil to do some thinking on his own account about the hows and whys of the physical world in which he lives.* To this end such subjects, and only such subjects, have been included as touch most closely the everyday life of the average pupil. In a word, the endeavor has been to make this book represent the practical, everyday physics which the average person needs to help him to adjust himself to his surroundings and to interpret his own experiences correctly.

But the conditions of modern life are changing at an astonishing rate and calling for the continuous revision of any text which would keep pace with them. For example, within the past ten years the internal-combustion engine has not only taken its place as an agent of equal importance with the steam engine in the world's industries but, what is more important, it has also come more fully into the daily life of the average man and woman than even the dynamo and motor have ever begun to do. The automobile is accordingly given fuller treatment in this new book than it has ever received before in any elementary physics text.

Again, man's conquest of the air, after centuries of failure, is not only the most significant advance, on the practical side, of the twentieth century, but the airplane now attracts the attention and excites the interest of almost every man, woman, and child. Accordingly, the principles underlying this advance, and the methods by which it was brought about, find as full treatment in this volume as is consistent

with the simplicity and clearness demanded in a beginning course in physics. The book may be used, if desired, even in the second year of the high school.

Further, the World War was responsible not only for extraordinary developments in physics but also for demonstrating, both to the American youth and to the leader of American industry, the necessity of the more intensive cultivation of physical science. These developments and these new demands, with which the authors came into the closest touch because of their service in the army both in this country and in France, have been fully reflected in this book, the emphasis, however, being placed upon developments which make for peace rather than for war.

As in preceding editions, the full-page inserts, though a very vital part of the book, are not a necessary and integral part of the course. They have been inserted, in more than double their former number, in order to add human and historic interest and to stimulate the pupil to look farther into a subject than his immediate assignment requires him to do. It is thought that they will be found to be an invaluable adjunct to the course.

Both the order and the treatment are in many places markedly different from those of preceding editions, and reflect the experience of the tens of thousands of teachers who have used this course, many of whom have assisted the authors with their suggestions. Especially in the problems have important improvements been made.

For the sake of indicating in what directions omissions may be made, if necessary, without interfering with continuity, paragraphs have here and there, as in former editions, been thrown into fine print. These paragraphs will be easily distinguished from the classroom experiments, which are in the same type. They are for the most part descriptions of physical appliances.

The authors are under great obligation to all of their friends who have assisted them in this work, particularly to their collaborator, Mr. W. R. Pyle; also to Mr. J. R. Towne of East High School, Minneapolis, Mr. C. F. Dutton, of the West High School of Commerce, Cleveland, Mr. E. Waite Elder, of the Eastside High School, Denver, Mr. C. E. Harris, of the East High School, Rochester, N. Y., Mr. Walter L. Barnum and Mr. Robert E. Hughes, of the Evanston High School, Evanston, Ill., and Dr. George de Bothezat, aëronautical expert of the Advisory Commission for Aëronautics.

R. A. MILLIKAN
H. G. GALE

THE UNIVERSITY OF CHICAGO

CONTENTS

CHAPTER PAGE

I. MEASUREMENT 1
Fundamental Units. Density

II. PRESSURE IN LIQUIDS 11
Liquid Pressure beneath a Free Surface. Pascal's Law. The Principle of Archimedes

III. PRESSURE IN AIR 26
Barometric Phenomena. Compressibility and Expansibility of Air. Pneumatic Appliances

IV. MOLECULAR MOTIONS 49
Kinetic Theory of Gases. Molecular Motions in Liquids. Molecular Motions in Solids

V. FORCE AND MOTION 57
Definition and Measurement of Force. Composition and Resolution of Forces. Gravitation. Falling Bodies. Newton's Laws

VI. MOLECULAR FORCES 90
Elasticity. Capillary Phenomena. Absorption of Gases

VII. WORK AND MECHANICAL ENERGY 105
Definition and Measurement of Work. Work and the Pulley. Work and the Lever. The Principle of Work. Power and Energy

VIII. THERMOMETRY; EXPANSION COEFFICIENTS 128
Thermometry. Expansion Coefficient of Gases. Expansion of Liquids and Solids. Applications of Expansion

IX. WORK AND HEAT ENERGY 144
Friction. Efficiency. Mechanical Equivalent of Heat. Specific Heat

X. CHANGE OF STATE 161
Fusion. Properties of Vapors. Hygrometry. Boiling. Artificial Cooling. Industrial Applications

CHAPTER PAGE

XI. THE TRANSFERENCE OF HEAT 203
Conduction. Convection. Radiation. Heating and Ventilating

XII. MAGNETISM 214
General Properties of Magnets. Terrestrial Magnetism

XIII. STATIC ELECTRICITY 225
General Facts of Electrification. Distribution of Charge. Potential and Capacity

XIV. ELECTRICITY IN MOTION 244
Detection of Electric Currents. Chemical Effects. Magnetic Effects. Measurement of Currents. Electric Bell and Telegraph. Resistance and Electromotive Force. Primary Cells. Secondary Cells. Heating Effects

XV. INDUCED CURRENTS 290
The Principle of the Dynamo and Motor. Dynamos. The Principle of the Induction Coil and Transformer

XVI. NATURE AND TRANSMISSION OF SOUND 319
Speed and Nature. Reflection, Reënforcement, and Interference

XVII. PROPERTIES OF MUSICAL SOUNDS 337
Musical Scales. Vibrating Strings. Fundamentals and Overtones. Wind Instruments

XVIII. NATURE AND PROPAGATION OF LIGHT 357
Transmission of Light. The Nature of Light

XIX. IMAGE FORMATION 378
Images formed by Lenses. Images in Mirrors. Optical Instruments

XX. COLOR PHENOMENA 402
Color and Wave Length. Spectra

XXI. INVISIBLE RADIATIONS 417
Radiation from a Hot Body. Electrical Radiations. Cathode and Röntgen Rays. Radioactivity

APPENDIX 437

INDEX 455

PORTRAITS OF PHYSICISTS AND ILLUSTRATIONS OF RECENT ACHIEVEMENTS IN PHYSICS

		PAGE
1.	The Navy-Curtiss Hydroplane, *NC-4* (In colors)	Frontispiece
2.	Archimedes	22
3.	The Details of a Submarine	23
4.	Otto von Guericke	32
5.	The Mercury-Diffusion Air Pump	33
6.	British Dirigible Airship *R-34* Arriving in America	44
7.	The United States Army Observation Balloon	45
8.	Galileo	72
9.	French 340-mm. Gun in Action	73
10.	Sir Isaac Newton	84
11.	The Cream Separator	85
12.	James Clerk-Maxwell	102
13.	Heinrich Rudolph Hertz	102
14.	A Gas Mask	103
15.	James Prescott Joule	122
16.	James Watt	122
17.	The *Rocket* and the *Virginian Mallet*	123
18.	Lord Kelvin (Sir William Thomson)	134
19.	The *Clermont* and the *Leviathan*	135
20.	A United States Dreadnaught in the Panama Canal	152
21.	The Vickers-Vimy Airplane	153
22.	A Tank	190
23.	The Liberty Motor	191
24.	Section of a Modern Automobile	198
25.	The Carburetor and an Ignition System	199
26.	William Gilbert	222
27.	The Sperry Gyrocompass	223
28.	Benjamin Franklin	230
29.	Franklin's Kite Experiment	231
30.	Count Alessandro Volta	240
31.	A Modern High-Tension Tower	241
32.	Hans Christian Oersted	246
33.	Joseph Henry	246
34.	Electromagnets	247

PAGE
35. André Marie Ampère 256
36. Huge Rotor 257
37. Samuel F. B. Morse 260
38. Diagrams of Morse Telegraph 261
39. Georg Simon Ohm 268
40. The Electric Iron and Fuses 269
41. Michael Faraday 290
42. Induction Motor 291
43. Alexander Graham Bell 316
44. Thomas A. Edison 316
45. Guglielmo Marconi 316
46. Orville Wright 316
47. The Original Wright Glider and the First Power-Driven Airplane 317
48. Sound Waves of Spoken Words 346
49. Sound Ranging Record of the End of the War 347
50. A. A. Michelson 358
51. Lord Rayleigh (John William Strutt) 358
52. Henry A. Rowland 358
53. Sir William Crookes 358
54. X-Ray Picture of the Human Thorax 359
55. Christian Huygens 364
56. The Great Telescope of the Yerkes Observatory 365
57. Section of a "Movie" Film 386
58. Arthur L. Foley's Sound-Wave Photographs 387
59. Three-Color Printing (In colors) 408
60. The Wireless Telephone utilized in Aviation 424
61. Cinematograph Film of a Bullet fired through a Soap Bubble . . 425
62. Sir Joseph Thomson 430
63. Amplifier, and Diagram of Receiving and Amplifying Set 431
64. William Conrad Röntgen 436
65. Antoine Henri Becquerel 436
66. Madame Curie 436
67. E. Rutherford 436
68. X-Ray Spectra 437

PRACTICAL PHYSICS

CHAPTER I

MEASUREMENT

Fundamental Units

1. Introductory. A certain amount of knowledge about familiar things comes to us all very early in life. We learn almost unconsciously, for example, that stones fall and balloons rise, that the teakettle stops boiling when removed from the fire, that telephone messages travel by electric currents, etc. The aim of the study of physics is to set us to thinking about *how* and *why* such things happen, and, to a less degree, to acquaint us with other happenings which we may not have noticed or heard of previously.

Most of our accurate knowledge about natural phenomena has been acquired through careful measurements. We can measure three fundamentally different kinds of quantities, — length, mass, and time, — and we shall find that all other measurements may be reduced to these three. Our first problem in physics is, then, to learn something about the units in terms of which all our physical knowledge is expressed.

2. The historic standard of length. Nearly all civilized nations have at some time employed a unit of length the name of which bore the same significance as does *foot* in English. There can scarcely be any doubt, therefore, that in each country this unit has been derived from the length of

the human foot. It is probable that in England, after the yard (a unit which is supposed to have represented the length of the arm of King Henry I) became established as a standard, the foot was arbitrarily chosen as one third of this standard yard. In view of such an origin it will be clear why no agreement existed among the units in use in different countries.

3. Relations between different units of length. It has also been true, in general, that in a given country the different units of length in common use (such, for example, as the inch, the hand, the foot, the fathom, the rod, the mile, etc.) have been derived either from the lengths of different members of the human body or from equally unrelated magnitudes, and in consequence have been connected with one another by different, and often by very awkward, multipliers. Thus, there are 12 inches in a foot, 3 feet in a yard, $5\frac{1}{2}$ yards in a rod, 1760 yards in a mile, etc.

4. Relations between units of length, area, volume, and mass. A similar and even worse complexity exists in the relations of the units of length to those of area, capacity, and mass. Thus, there are $272\frac{1}{4}$ square feet in a square rod; $57\frac{3}{4}$ cubic inches in a quart, and $31\frac{1}{2}$ gallons in a barrel. Again, the pound, instead of being the mass of a cubic inch or a cubic foot of water, or of some other common substance, is the mass of a cylinder of platinum, of inconvenient dimensions, which is preserved in London.

5. Origin of the metric system. At the time of the French Revolution the extreme inconvenience of existing weights and measures, together with the confusion arising from the use of different standards in different localities, led the National Assembly of France to appoint a commission to devise a more logical system. The result of the labors of this commission was the present metric system, which was introduced in France in 1793 and has since been adopted by the governments of most civilized nations except those of Great Britain and the

United States; and even in these countries its use in scientific work is practically universal. The World War has done much to speed its adoption in these countries.

6. The standard meter. The standard *length* in the metric system is called the *meter.* It is the distance, at the freezing temperature, between two transverse parallel lines ruled on a bar of platinum-iridium (Fig. 1), which is kept at the International Bureau of Weights and Measures at Sèvres, near Paris. *This distance is 39.37 inches.*

In order that this standard length might be reproduced if lost, the commission attempted to make it one ten-millionth

Fig. 1. The standard meter

of the distance from the equator to the north pole, measured on the meridian of Paris. But since later measurements have thrown some doubt upon the exactness of the commission's determination of this distance, we now define the meter, not as any particular fraction of the earth's quadrant, but simply as the distance between the scratches on the bar mentioned above. On account of its more convenient size, the centimeter, one one-hundredth of a meter, is universally used, for scientific purposes, as the fundamental unit of length.

7. Metric standard capacity. The standard unit of capacity is called the *liter.* It is the volume of a cube which is one tenth of a meter (about 4 inches) on a side. *The liter is therefore*

equal to 1000 cubic centimeters (cc.). It is equivalent to 1.057 quarts. A liter and a quart are therefore roughly equivalent measures.

8. The metric standard of mass. In order to establish a connection between the unit of length and the unit of mass, the commission directed a committee of the French Academy to prepare a cylinder of platinum which should have the same weight as a liter of water at its temperature of greatest density, namely, 4° Centigrade (39° Fahrenheit). An exact equivalent of this cylinder, made of platinum-iridium and kept at Sèvres with the standard meter, now represents the standard of mass in the metric system. It is called the *standard kilogram* and is equivalent to about 2.2 pounds. One one-thousandth of this mass was adopted as the fundamental unit of mass and was named the *gram.* For practical purposes, therefore, the *gram may be taken as equal to the mass of one cubic centimeter of water.*

9. The other metric units. The three standard units of the metric system — the meter, the liter, and the gram — have decimal multiples and submultiples, so that every unit of length, volume, or mass is connected with the unit of next higher denomination by an invariable multiplier, namely, ten.

The names of the multiples are obtained by adding the Greek prefixes, *deka* (ten), *hecto* (hundred), *kilo* (thousand); while the submultiples are formed by adding the Latin prefixes, *deci* (tenth), *centi* (hundredth), and *milli* (thousandth). Thus:

1 dekameter = 10 meters	1 decimeter = $\frac{1}{10}$ meter
1 hectometer = 100 meters	1 centimeter = $\frac{1}{100}$ meter
1 kilometer = 1000 meters	1 millimeter = $\frac{1}{1000}$ meter

The most common of these units, with the abbreviations which will henceforth be used for them, are the following:

meter (m.)	millimeter (mm.)	gram (g.)
kilometer (km.)	liter (l.)	kilogram (kg.)
centimeter (cm.)	cubic centimeter (cc.)	milligram (mg.)

10. Relations between the English and metric units. The following table, which is inserted for reference, gives the relation between the most common English and metric units.

1 inch (in.)	= 2.54 cm.	1 cm.	= .3937 in.
1 foot (ft.)	= 30.48 cm.	1 m.	= 1.094 yd. = 39.37 in.
1 mile (mi.)	= 1.609 km.	1 km.	= .6214 mi.
1 grain	= 64.8 mg.	1 g.	= 15.44 grains
1 oz. av.	= 28.35 g.	1 g.	= .0353 oz.
1 lb. av.	= .4536 kg.	1 kg.	= 2.204 lb.

The relations 1 in. = 2.54 cm., 1 m. = 39.37 in., 1 kilo (kg.) = 2.2 lb., 1 km. = .62 mi. should be memorized. Portions of a centimeter and of an inch scale are shown together in Fig. 2.

11. The standard unit of time. The *second* is taken among all civilized nations as the standard unit of time. It is $\frac{1}{86400}$ part of the time from noon to noon.

12. The three fundamental units. It is evident that measurements of both area and volume may be reduced simply

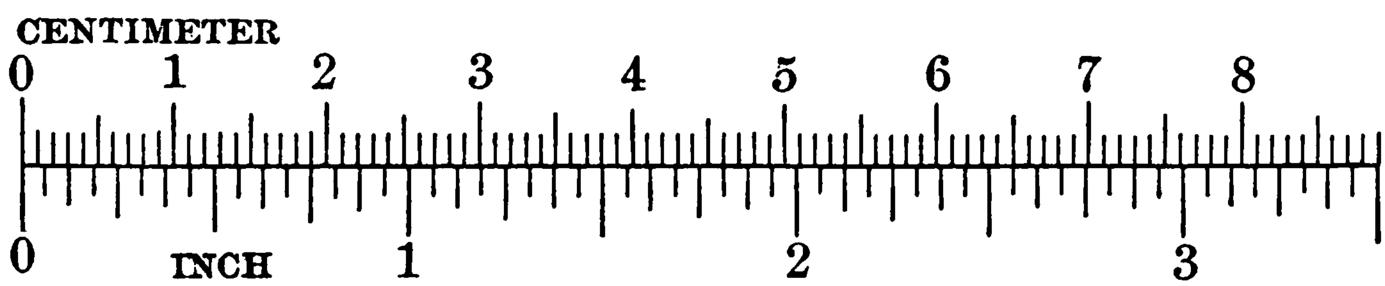


FIG. 2. Centimeter and inch scales

to measurements of length; for an area is expressed as the product of two lengths, and a volume as the product of three lengths. For these reasons the units of area and volume are looked upon as *derived* units, depending on one *fundamental* unit, the unit of length.

Now it is found that just as measurements of area and of volume can be reduced to measurements of length, so the determination of any measurable quantities, such as the pressure in a steam boiler, the velocity of a moving train,

the amount of electricity consumed by an electric lamp, the amount of magnetism in a magnet, etc., can be reduced simply to measurements of length, mass, and time. Hence *the centimeter, the gram, and the second are considered the three fundamental units.* Whenever any measurement has been reduced to its equivalent in terms of centimeters, grams, and seconds, it is said, for short, to be expressed in C.G.S. (Centimeter-Gram-Second) units.

13. Measurement of length. Measuring the length of a body consists simply in comparing its length with that of the standard meter bar kept at the International Bureau. In order that this may be done conveniently, great numbers of rods of the same length as this standard meter bar have been made and scattered all over the world. They are our common meter sticks. They are divided into 10, 100, or 1000 equal parts, great care being taken to have all the parts of exactly the same length. The method of making a measurement with such a bar is more or less familiar to everyone.

14. Measurement of mass. Similarly, measuring the mass of a body consists in comparing its mass with that of the standard kilogram. In order that this might be done conveniently, it was first necessary to construct bodies of the same mass as this kilogram, and then to make a whole series of bodies whose masses were $\frac{1}{2}$, $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$, etc. of the mass of this kilogram; in other words, to construct a set of standard masses commonly called a *set of weights.*

With the aid of such a set of standard masses the determination of the mass of any unknown body is made by first placing the body upon the pan A (Fig. 3) and counterpoising with shot, paper, etc., then replacing the unknown body by as many of the standard masses as are required to bring the pointer back to O again. The mass of the body is equal to the sum of these standard masses. This rigorously correct method of weighing is called the *method of substitution.*

If a balance is well constructed, however, a weighing may usually be made with sufficient accuracy by simply placing the unknown body upon one pan and finding the sum of the standard masses which must then be placed upon the other pan to bring the pointer again to O. This is the usual method of weighing. It gives correct results, however, only when the knife-edge C is exactly midway between the points of support m and n of the two pans. The method of substitution, on the other hand, is independent of the position of the knife-edge. *It is customary to consider that the mass of a body determined as here indicated is a measure of the quantity of matter which it contains.*

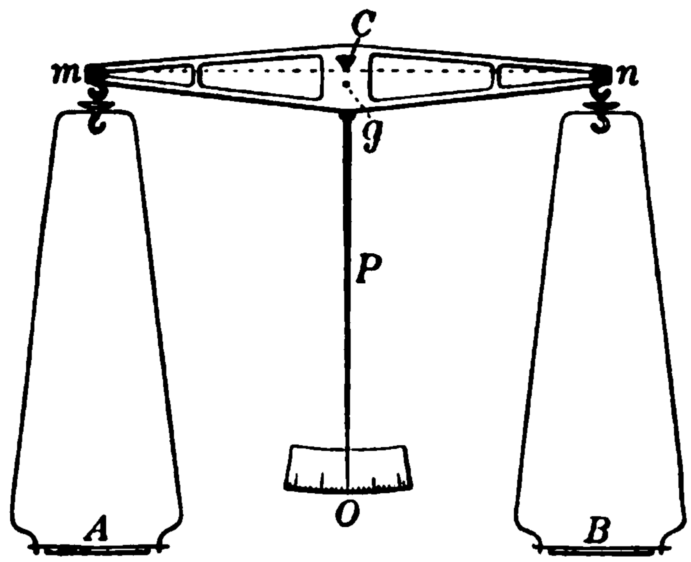


FIG. 3. The simple balance

QUESTIONS AND PROBLEMS

1. The 200-meter run at the Olympic games corresponds to the 220-yard run in our local games. Which is the longer and how much?

2. The French 75-mm. guns have what diameter in inches?

3. The Twentieth Century Limited runs from New York to Chicago (967 mi.) in 20 hr. Find its average speed in miles per hour.

4. Name as many advantages as you can which the metric system has over the English system. Can you think of any disadvantages?

5. What must you do to find the capacity in liters of a box when its length, breadth, and depth are given in meters? to find the capacity in quarts when its dimensions are given in feet?

6. Find the number of millimeters in 6 km. Find the number of inches in 4 mi. Which is the easier?

7. With a Vickers-Vimy biplane Captain Alcock and Lieutenant Brown completed, on June 15, 1919, the first nonstop transatlantic flight of 1890 miles from Newfoundland to Ireland in 15 hr. 57 min. How many miles per hour? How many kilometers per hour?

8. Find the capacity in liters of a box .5 m. long, 20 cm. wide, and 100 mm. deep.

Density

15. Definition of density. When equal volumes of different substances, such as lead, wood, iron, etc., are weighed in the manner described above, they are found to have widely different masses. The term "density" is used to denote *the mass, or quantity of matter, per unit volume.*

Thus, for example, in the English system the cubic foot is the unit of volume and the pound the unit of mass. Since 1 cubic foot of water is found to weigh 62.4 pounds, we say that in the English system *the density of water is* 62.4 *pounds per cubic foot.*

In the C.G.S. system the cubic centimeter is taken as the unit of volume and the gram as the unit of mass. Hence we say that in this system the density of water is 1 gram per cubic centimeter, for it will be remembered that the gram was taken as the mass of 1 cubic centimeter of water. Unless otherwise expressly stated, density is now universally understood to mean density in C.G.S. units; that is, *the density of a substance is the mass in grams of* 1 *cubic centimeter of that substance.* For example, if a block of cast iron 3 cm. wide, 8 cm. long, and 1 cm. thick weighs 177.6 g., then, since there are 24 cc. in the block, the mass of 1 cc., that is, the density, is equal to $\frac{177.6}{24}$, or 7.4 g. per cubic centimeter.

The density of some of the most common substances is given in the following table:

Densities of Solids

(In grams per cubic centimeter)

Aluminium	2.58	Nickel	8.9
Brass	8.5	Oak	.8
Copper	8.9	Pine	.5
Cork	.24	Platinum	21.4
Glass	2.6	Silver	10.5
Gold	19.3	Tin	7.3
Iron (cast)	7.4	Tungsten	19.6
Lead	11.3	Zinc	7.1

Densities of Liquids

(In grams per cubic centimeter)

Alcohol	.79	Hydrochloric acid	1.27
Carbon bisulphide	1.29	Mercury	13.6
Glycerin	1.26	Gasoline	.75

16. Relation between mass, volume, and density. Since the mass of a body is equal to the total number of grams which it contains, and since its volume is the number of cubic centimeters which it occupies, the mass of 1 cubic centimeter is evidently equal to the total mass divided by the volume. Thus, if the mass of 100 cubic centimeters of iron is 740 grams, the density of iron must equal $740 \div 100 = 7.4$ grams to the cubic centimeter. To express this relation in the form of an equation, let M represent the mass of a body, that is, its total number of grams; V its volume, that is, its total number of cubic centimeters; and D its density, that is, the number of grams in 1 cubic centimeter; then

$$D = \frac{M}{V}. \tag{1}$$

This equation merely states the definition of density in algebraic form.

17. Distinction between density and specific gravity. The term "specific gravity" is used to denote *the ratio between the weight of a body and the weight of an equal volume of water.**

Thus, if a certain piece of iron weighs 7.4 times as much as an equal volume of water, its specific gravity is 7.4. But since the density of water in C.G.S. units is 1 gram per cubic centimeter, the density of iron in that system is 7.4 grams per cubic centimeter. It is clear, then, that *density in C.G.S. units is numerically the same as specific gravity.*

* For the present purpose the terms "weight" and "mass" may be used interchangeably. They are in general numerically equal, although an important distinction between them will be developed in § 73. Weight is in reality a *force* rather than a *quantity of matter.*

Specific gravity is the same in all systems, since it simply expresses how many times heavier a body is than an equal volume of water. Density, however, which we have defined as the mass per unit volume, is different in different systems. Thus, in the English system the density of iron is 462 pounds per cubic foot (7.4×62.4), since we have found that water weighs 62.4 pounds per cubic foot and that iron weighs 7.4 times as much as an equal volume of water.*

QUESTIONS AND PROBLEMS †

1. A liter of milk weighs 1032 grams. What is its density and its specific gravity?

2. A ball of yarn was squeezed into $\frac{1}{4}$ of its original bulk. What effect did this produce upon its mass, its volume, and its density?

3. If a wooden beam is $30 \times 20 \times 500$ cm. and has a mass of 150 kg., what is the density of wood?

4. Would you attempt to carry home a block of gold the size of a peck measure? (Consider a peck equal to 8 l. See table, p. 8.)

5. What is the mass of a liter of alcohol?

6. How many cubic centimeters in a block of brass weighing 34 g.?

7. What is the weight in metric tons of a cube of lead 2 m. on an edge? (A metric ton is 1000 kilos, or about 2200 lb.)

8. Find the volume in liters of a block of platinum weighing 45.5 kilos.

9. One kilogram of alcohol is poured into a cylindrical vessel and fills it to a depth of 8 cm. Find the cross section of the cylinder.

10. Find the length of a lead rod 1 cm. in diameter and weighing 1 kg.

* Laboratory exercises on length, mass, and density measurements should accompany or follow this chapter. See, for example, Experiments 1, 2, and 3 of the authors' Manual.

† Questions and problems to supplement this chapter and all following chapters are given in the Appendix, page 437.

CHAPTER II

PRESSURE IN LIQUIDS

Liquid Pressure beneath a Free Surface

18. Force beneath the surface of a liquid. We are all conscious of the fact that in order to lift a kilogram of mass we must exert an upward pull. Experience has taught us that the greater the mass, the greater the force which we must exert. The force is commonly taken as numerically equal to the mass lifted. This is called the *weight measure* of a force. *A push or pull which is equal to that required to support a gram of mass is called a gram of force.* Thus, five grams of force are needed to lift a new five-cent piece.

To investigate the nature of the forces beneath the free surface of a liquid we shall use a pressure gauge of the form shown in Fig. 4. If the rubber diaphragm which is stretched across the mouth of a thistle tube A is pressed in lightly with the finger, the drop of ink B will be observed to move forward in the tube T, but it will return again to its first position as soon as the finger is removed. If the pressure of the finger is increased, the drop will move forward a greater distance than before. We may therefore take the amount of motion of the drop as a measure of the force acting on the diaphragm.

Now let A be pushed down first 2 cm., then 4 cm., then 8 cm. below the surface of the water (Fig. 4). The motion of the index B will show that the upward force continually increases as the depth increases.

Careful measurements made in the laboratory will show that *the force is directly proportional to the depth.**

* It is recommended that quantitative laboratory work on the law of depths and on the use of manometers accompany this discussion. See, for example, Experiments 4 and 5 of the authors' Manual.

Let the diaphragm A (Fig. 4) be pushed down to some convenient depth (for example, 10 centimeters) and the position of the index noted. Then let it be turned sidewise so that its plane is vertical (see a, Fig. 4), and adjusted in position until its center is exactly 10 centimeters beneath the surface, that is, until the *average* depth of the diaphragm is the same as before. The position of the index will show that the force is also exactly the same as before.

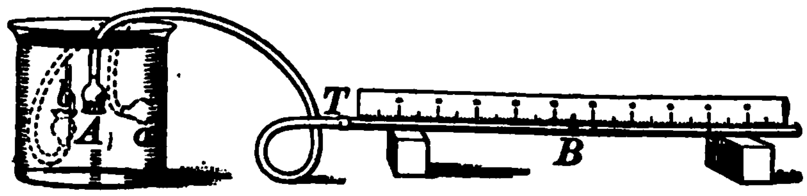


FIG. 4. Gauge for measuring liquid pressure

Let the diaphragm then be turned to the position b, so that the gauge measures the *downward* force at a depth of 10 centimeters. The index will show that this force is again the same.

We conclude, therefore, that *at a given depth a liquid presses up and down and sidewise on a given surface with exactly the same force.*

19. Magnitude of the force. If a vessel like that shown in Fig. 5 is filled with a liquid, the force against the bottom is obviously equal to the weight of the column of liquid resting upon the bottom. Thus, if F represents this force in grams, A the area in square centimeters, h the depth in centimeters, and d the density in grams per cubic centimeter, we shall have

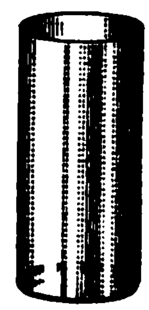


FIG. 5

$$F = Ahd. \qquad (1)$$

Since, as was shown by the experiment of the preceding section, the force is the same in all directions at a given depth, we have the following general rule:

The force which a liquid exerts against any surface is equal to the area of the surface times its average depth times the density of the liquid.

It is important to remember that "average depth" means the vertical distance from the level of the free surface to the center of the area in question.

20. Pressure in liquids. Thus far attention has been confined to the total force exerted by a liquid against the *whole* of a given surface. It is often more convenient to imagine the surface divided into square centimeters or square inches, and then to consider the force on one of these units of area. In physics the word "pressure" is used exclusively to denote the *force per unit area.* Pressure is thus a measure of the *intensity* of the force acting on a surface, and does not depend at all on the area of the surface. Since, by § 19, $F = Ahd$, and since by definition the pressure p is equal to the force per unit area, we have

$$p = \frac{F}{A} = hd. \tag{2}$$

Therefore *the pressure at a depth of h centimeters below the surface of a liquid of density d is hd grams per square centimeter.*

If the height is given in feet and the density in pounds per cubic foot, then the product hd gives pressure in pounds per square foot. Dividing by 144 gives the result in pounds per square inch.

21. Levels of liquids in connecting vessels. It is a perfectly familiar fact that when water is poured into a teapot it stands at exactly the same level in the spout as in the body of the teapot; or if it is poured into a number of connected vessels like those shown in Fig. 6, the surfaces of the liquid in the various vessels lie in the same horizontal plane. Now the pressure at c (Fig. 7) was shown by the experiment of § 18 to be equal to the density of the liquid times the depth cg. The pressure at o in the opposite direction must be equal to

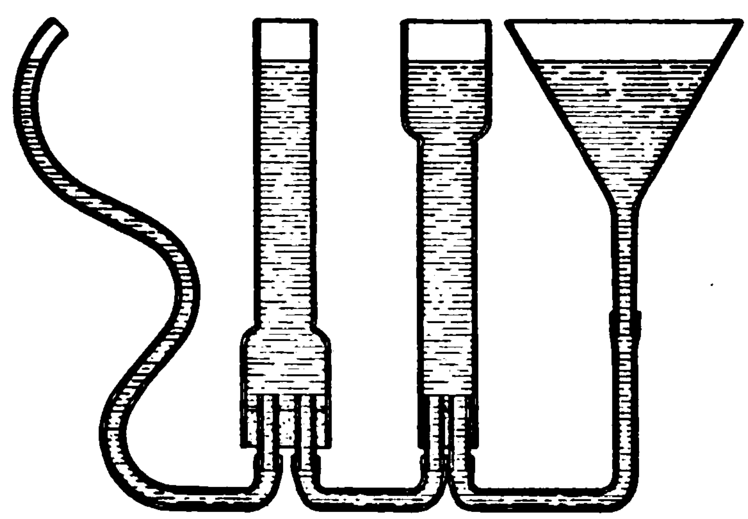


FIG. 6. Water level in communicating vessels

that at c, since the liquid does not tend to move in either direction. Hence the pressure at o must be ks times the density.

If water is poured in at s so that the height ks is increased, the pressure to the left at o becomes greater than the pressure to the right at c, and a flow of water takes place to the left until the heights are again equal.

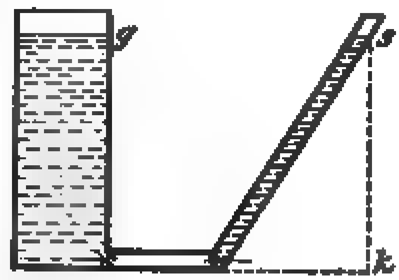


FIG. 7. Why water seeks its level

It follows from these observations on the level of water in connected vessels that *the pressure beneath the surface of a liquid depends simply on the vertical depth beneath the free surface, and not at all on the size or shape of the vessel.*

QUESTIONS AND PROBLEMS

1. Soundings at sea are made by lowering some kind of pressure gauge. When this gauge reads 1.3 kg. per square centimeter, what is the depth? (Density of sea water = 1.026.)

2. Kerosene is 0.8 as heavy as water (1 cu. ft. of water = 62.4 lb.). Find the pressure of the kerosene per square foot and per square inch on the bottom of an oil tank filled to a depth of 30 ft.

3. What pressure per square inch is required to force water to the top of the Woolworth building in New York City, 780 ft. high?

4. A swimming tank 50 ft. square is filled with water to a depth of 5 ft. Find the force of the water on the bottom; on one side.

5. If the areas of the surfaces AB in Fig. 8, (*1*) and (*2*), are the same, and if water is poured into each vessel at D till it stands at the same height above AB, how will the downward force on AB in Fig. 8, (*2*), compare with that in Fig. 8, (*1*)? Test your answer, if possible, by making AB a piece of cardboard and pouring water in at D, in each case, until the cardboard is forced off.

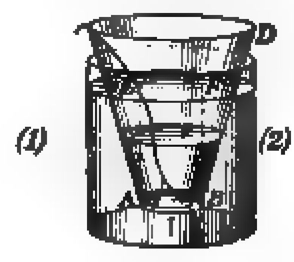


FIG. 8. Illustrating hydrostatic paradox

6. If the vessel shown in Fig. 10, (*1*) (p. 15), has a base of 200 sq. cm. and if the water stands 100 cm. deep, what is the total force on the bottom?

7. If the weight of the empty vessel in Fig. 10, (*1*), is small compared with the weight of the contained water, will the force required to lift the vessel and water be greater or less than the force exerted by the water against the bottom? Explain.

8. A whale when struck with a harpoon will often dive straight down as much as 400 fathoms (2400 ft.). If the body has an area of 1000 sq. ft., what is the total force to which it is subjected?

9. A hole 5 cm. square is made in a ship's bottom 7 m. below the water line. What force in kilograms is required to hold a board above the hole?

10. Thirty years ago standpipes were generally straight cylinders. To-day they are more commonly of the form shown in Fig. 9. What are the advantages of each form?

Fig. 9. A water reservoir

Pascal's Law

22. Transmission of pressure by liquids. From the fact that pressure within a free liquid depends simply upon the depth and density of the liquid, it is possible to deduce a very surprising conclusion, which was first stated by the famous French scientist, mathematician, and philosopher, Pascal (1623–1662).

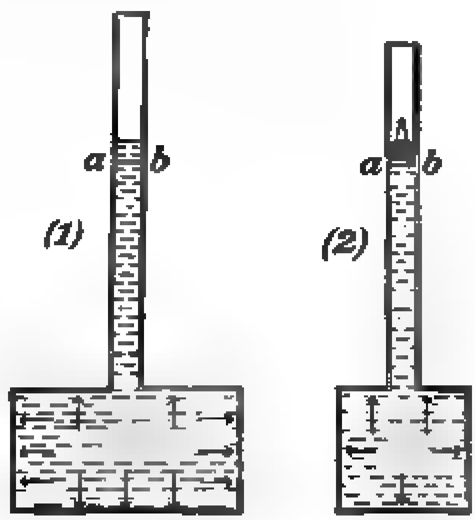


Fig. 10. Proof of Pascal's law

Let us imagine a vessel of the shape shown in Fig. 10, (*1*), to be filled with water up to the level *ab*. For simplicity let the upper portion be assumed to be 1 square centimeter in cross section. Since the density of water is 1, the force with which it presses against any square centimeter of the interior surface which is *h* centimeters beneath the level *ab* is *h* grams. Now let 1 gram of water (that is, 1 cubic centimeter) be poured into the tube. Since each square centimeter of surface, which before was *h* centimeters beneath the level of the

water in the tube, is now $h+1$ centimeters beneath this level, the new pressure which the water exerts against it is $h+1$ grams; that is, applying 1 gram of force to the square centimeter of surface *ab* has added 1 gram to the force exerted by the liquid against each square centimeter of the interior of the vessel. Obviously it can make no difference whether the pressure which was applied to the surface *ab* was due to a weight of water or to a piston carrying a load, as in Fig. 10, (*2*), or to any other cause whatever. We thus arrive at Pascal's conclusion that *pressure applied anywhere to a body of confined liquid is transmitted undiminished to every portion of the surface of the containing vessel.*

23. Multiplication of force by the transmission of pressure by liquids. Pascal himself pointed out that with the aid of the principle stated above we ought to be able to transform a very small force into one of unlimited magnitude. Thus, if the area of the cylinder *ab* (Fig. 11) is 1 sq. cm., while that of the cylinder *AB* is 1000 sq. cm., a force of 1 kg. applied to *ab* would be transmitted by the liquid so as to act with a force of 1 kg. on each square centimeter of the surface *AB*. Hence the total upward force exerted against the piston *AB* by the 1 kg. applied at *ab* would be 1000 kg. Pascal's own words are as follows: "A vessel full of water is a new principle in mechanics, and a new machine for the multiplication of force to any required extent, since one man will by this means be able to move any given weight."

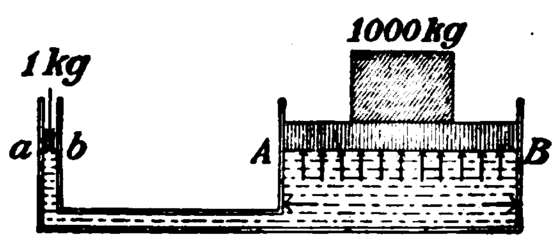


FIG. 11. Multiplication of force by transmission of pressure

24. The hydraulic press. The experimental proof of the correctness of the conclusions of the preceding paragraph is furnished by the hydraulic press, an instrument now in common use for subjecting to enormous pressures paper, cotton, etc. and for punching holes through iron plates, testing the strength of iron beams, extracting oil from

seeds, making dies, embossing metal, etc. Hydraulic presses of great power have been designed for use in steel works to replace huge steam hammers. Compressing forces of 10,000 tons or more are thus obtained. Much cold steel, as well as hot, is now pressed instead of hammered.

Such a press is represented in section in Fig. 12. As the small piston p is raised, water from the cistern C enters the piston chamber through the valve v. As soon as the downstroke begins, the valve v closes, the valve v' opens, and the pressure applied on the piston p is transmitted through the tube K to the large reservoir, where it acts on the large cylinder P.

The force exerted upon P is as many times that applied to p as the area of P is times the area of p.

FIG. 12. Diagram of a hydraulic press

25. No gain in the product of force times distance. It should be noticed that, while the force acting on AB (Fig. 11) is 1000 times as great as the force acting on ab, the distance through which the piston AB is pushed up in a given time is but $\frac{1}{1000}$ of the distance through which the piston ab moves down. For forcing ab down a distance of 1 centimeter crowds but 1 cubic centimeter of water over into the large cylinder, and this additional cubic centimeter can raise the level of the water there but $\frac{1}{1000}$ centimeter. We see, therefore, that the product of the force acting by the distance moved is precisely the same at both ends of the machine. This important conclusion will be found in our future study to apply to all machines.

26. The hydraulic elevator. Another very common application of the principle of transformation of pressure by liquids is found in the hydraulic elevator. The simplest form of such an elevator is shown in Fig. 13. The cage A is borne on the top of a long piston P which runs in a cylindrical pit C of the same depth as the height to which the carriage must ascend. Water enters the pit either directly from the water mains, m, of the city's supply or, if this does not furnish sufficient pressure, from a special reservoir on top of the building. When the elevator boy pulls *up* on the cord cc, the valve v opens so as to make connection from m into C. The elevator then ascends. When cc is pulled *down*, v turns so as to permit the water in C to escape into the sewer. The elevator then descends.

Fig. 13 Fig. 14

Diagrams of hydraulic elevators

Where speed is required the motion of the piston is communicated indirectly to the cage by a system of pulleys like that shown in Fig. 14. With this arrangement a foot of upward motion of the piston P causes the counterpoise D of the cage to descend 2 feet, for it is clear from the figure that when the piston goes up 1 foot, enough rope must be pulled over the fixed pulley p to lengthen each of the two strands a and b 1 foot. Similarly, when the counterpoise descends 2 feet, the cage ascends 4 feet. Hence the cage moves four times as fast and four times

as far as the piston. The elevators in the Eiffel Tower in Paris are of this sort. They have a total travel of 420 feet and are capable of lifting 50 people 400 feet per minute. The cylinder *C* and piston *P* are often not in a pit but lie in a horizontal position. Most modern elevators are electric rather than hydraulic.

27. City water supply. Fig. 15 illustrates the method by which a city is often supplied with water from a distant source. The aqueduct from the lake *a* passes under a road *r*, a brook *b*, and a hill *H*, and into a reservoir *e*, from which it is forced by the pump *p* into the standpipe *P*, whence it is distributed to the houses of the city. If a static condition prevailed in

FIG. 15. City water supply from lake

the whole system, then the water level in *e* would of necessity be the same as that in *a*, and the level in the pipes of the building *B* would be the same as that in the standpipe *P*. But when the water is flowing, the friction of the mains causes the level in *e* to be somewhat less than that in *a*, and that in *B* less than that in *P*. It is on account of the friction both of the air and of the pipes that the fountain *f* does not rise nearly as high as the ideal limit shown in the figure.

QUESTIONS AND PROBLEMS

1. A jug full of water may often be burst by striking a blow on the cork. If the surface of the jug is 200 sq. in. and the cross section of the cork 1 sq. in., what total force acts on the interior of the jug when a 10-lb. blow is struck on the cork?

2. How does your city get its water? How is the pressure in the pipes maintained?

3. If the water pressure in the city mains is 70 lb. to the square inch, how high above the town is the top of the water in the standpipe?

4. The cross-sectional areas of the pistons of a hydraulic press were 3 sq. in. and 60 sq. in. How great a weight would the large piston sustain if 75 lb. were applied to the small one?

5. The diameters of the pistons of a hydraulic press were 2 in. and 20 in. What force would be produced upon the large piston by 50 lb. on the small one?

6. The water pressure in the city mains is 80 lb. to the square inch. The diameter of the piston of a hydraulic elevator of the type shown in Fig. 13 is 10 in. If friction could be disregarded, how heavy a load could the elevator lift? If 30% of the ideal value must be allowed for frictional loss, what load will the elevator lift?

7. Suppose a tube 5 mm. square and 200 cm. long is inserted into the top of a box 20 cm. on a side and filled with water; what will be the total force on the bottom of the box? on the top?

THE PRINCIPLE OF ARCHIMEDES *

28. Apparent loss of weight of a body in a liquid. The preceding experiments have shown that an upward force acts against the bottom of any body immersed in a liquid. If the body is a boat, cork, piece of wood, or any body which floats, it is clear that, since it is in equilibrium, this upward force must be equal to the weight of the [illegible]dy. Even if the body does not float, everyday observati[illegible]hows that it still loses a portion of its natural weight, f[illegible] is well known that it is easier to lift a stone under w[illegible]in air, or, again, that a man in a bathtub can sup[illegible]ight by pressing lightly against the botto[illegible] fingers. It was indeed this very observation wh[illegible]t led the old Greek philosopher Archimedes (287[illegible]B.C.) (see opposite page 22) to the discovery of the [illegible] law which governs the loss of weight of a body i[illegible]id.

* A laboratory exercise on the exp[illegible]al proof of Archimedes' principle should either precede or accom[illegible]y this discussion. See, for example, Experiment 6 of the authors' Manual.

Hiero, the tyrant of Syracuse, had ordered a gold crown made, but suspected that the artisan had fraudulently used silver as well as gold in its construction. He ordered Archimedes to discover whether or not this were true. How to do so without destroying the crown was at first a puzzle to the old philosopher. While in his daily bath, noticing the loss of weight of his own body, it suddenly occurred to him that *any body immersed in a liquid must apparently lose a weight equal to the weight of the displaced liquid.* He is said to have jumped at once to his feet and rushed through the streets of Syracuse crying, "Eureka! Eureka!" (I have found it! I have found it!)

29. Theoretical proof of Archimedes' principle. It is probable that Archimedes, with that faculty which is so common among men of great genius, saw the truth of his conclusion without going through any logical process of proof. Such a proof, however, can easily be given. Thus, since the upward force on the bottom of the block *abcd* (Fig. 16) is equal to the weight of the column of liquid *obce*, and since the downward force on the top of this block equal to the weight of the column of liquid *oade*, it is clear that the upward force must exceed the downward force by the weight of the column of liquid *abcd*. Archimedes' principle may be stated thus:

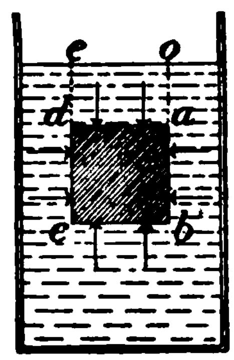


FIG. 16. Proof that an immersed body is buoyed up by a force equal to the weight of the displaced liquid

The buoyant [illegible]ted by a liquid is exactly equal to the weight of the displa[illegible]uid.

The reasoning is exactly the same, no matter what may be the nature of the liquid in which the body is immersed, nor how far the body may be beneath the surface. Further, if the body weighs more than the liquid which it displaces, it must

sink, for it is urged down with the force of its own weight, and up with the lesser force of the weight of the displaced liquid. But if it weighs less than the displaced liquid, then the upward force due to the displaced liquid is greater than its own weight, and consequently it must rise to the surface. When it reaches the surface, the downward force on the top of the block, due to the liquid, becomes zero. The body must, however, continue to rise until the upward force on its bottom is equal to its own weight. But this upward force is always equal to the weight of the displaced liquid, that is, to the weight of the column of liquid *mbcn* (Fig. 17). Hence

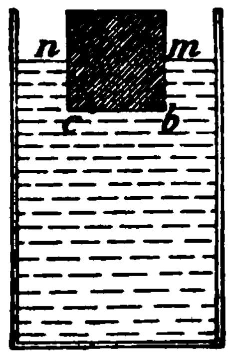


Fig. 17. Proof that a floating body is buoyed up by a force equal to the weight of the displaced liquid

A floating body must displace its own weight of the liquid in which it floats.

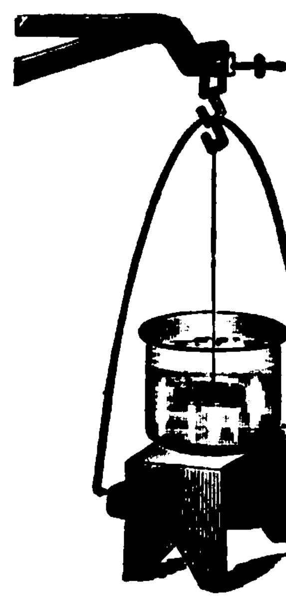


Fig. 18. Method of weighing a body under water

This statement is embraced in the statement of Archimedes' principle, for a body which floats has lost its whole weight.

30. Specific gravity of a heavy solid. The specific gravity of a body is by definition the ratio of its weight to the weight of an equal volume of water (§ 17). Since a submerged body displaces a volume of water equal to its own volume, however irregular it may be,

$$\text{Specific gravity of body} = \frac{\text{Weight of body}}{\text{Weight of water displaced}}$$

Making application of Archimedes' principle, we have

$$\text{Specific gravity of body} = \frac{\text{Weight of body}}{\text{Loss of weight in water}}$$

Fig. 18 shows a common method of weighing under water.

Archimedes (287–212 b.c.)

(Bust in Naples Museum)

The celebrated geometrician of antiquity; lived at Syracuse, Sicily; first made a determination of π and computed the area of the circle; discovered the laws of the lever and was author of the famous saying, "Give me where I may stand and I will move the world", discovered the laws of flotation; invented various devices for repelling the attacks of the Romans in the siege of Syracuse, on the capture of the city, while in the act of drawing geometrical figures in a dish of sand, he was killed by a Roman soldier to whom he cried out, "Don't spoil my circle"

The Details of a Submarine

The submarine, one of the newest of marine inventions, is a simple application of the principle of Archimedes, — one of the oldest principles of physics. In order to submerge, the submarine allows water to enter her ballast tanks until the total weight of the boat and contents becomes nearly as great as that of the water she is able to displace. The boat is then almost submerged. When she is under headway in this condition, a proper use of the horizontal, or diving, rudders sends her beneath the surface, or, if submerged, brings her to the surface, so that she can scan the horizon with her periscope. The whole operation takes but a few seconds. When the submarine wishes to come to the surface for recharging her batteries or for other purposes, she blows compressed air into her ballast tanks, thus driving the water out of them. Submarines are propelled on the surface by Diesel oil engines; underneath the surface, by storage batteries and electric motors

31. Specific gravity of a solid lighter than water. If the body is too light to sink of itself, we may still obtain the weight of the equal volume of water by forcing it beneath the surface with a sinker. Thus, suppose w_1 represents the weight on the right pan of the balance when the body is in air and the sinker in water, as in Fig. 19, while w_2 is the weight on the right pan when both body and sinker are under water. Then $w_1 - w_2$ is obviously the buoyant effect of the water on the body alone and is therefore equal to the weight of the displaced water.

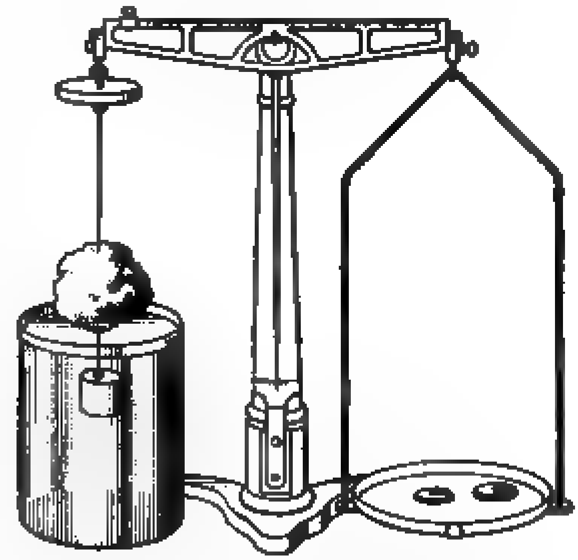


FIG. 19. Method of finding specific gravity of a light solid

32. Specific gravity of liquids by the hydrometer method. The commercial hydrometer such as is now in common use for testing the specific gravity of alcohol, milk, acids, sugar solutions, etc. is of the form shown in Fig. 20. The stem is calibrated by trial so that the specific gravity of any liquid may be read upon it directly. The principle involved is that a floating body sinks until it displaces its own weight. By making the stem very slender the sensitiveness of the instrument may be made very great. Why?

33. Specific gravity of liquids by "loss of weight" method. If any suitable solid be weighed, first in air, then in water, and then in a liquid of unknown specific gravity, by the principle of Archimedes the loss of weight in the liquid is equal to the weight of the liquid displaced, and the loss in water is equal to the weight of the water

FIG. 20. Constant-weight hydrometer

displaced. If we divide the loss of weight in the liquid by the loss of weight in water, we are dividing the weight of a given volume of liquid by the weight of an equal volume of water. Therefore,

*To find the specific gravity of a liquid, divide the loss of weight of some solid in it by the loss of weight of the same body in water.**

QUESTIONS AND PROBLEMS

1. Let a vessel of water, together with an object heavier than water, be counterpoised as in Fig. 21 (position *a*). Now if the object be placed inside the vessel of water (position *b*), will the scales remain balanced? Predict the result and then try the experiment.

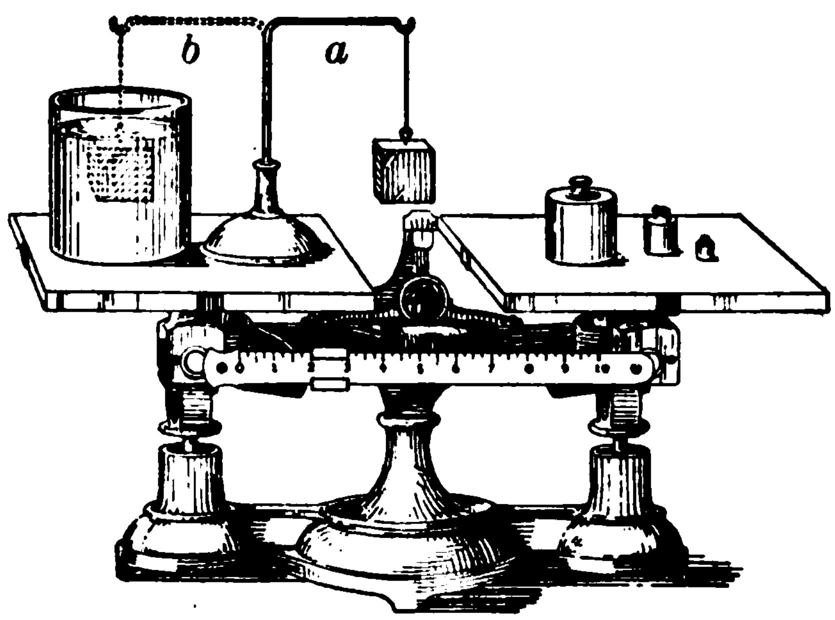


FIG. 21

2. Does the weight apparently lost by a submerged body depend upon its volume or its weight? Explain.

3. A brick lost 1 lb. when submerged 1 ft. deep; how much would it lose if suspended 3 ft. deep?

4. Will a boat rise or sink deeper in the water as it passes from a river to the ocean?

5. A fish lies perfectly motionless near the center of an aquarium. What is the average density of the fish? Explain.

6. Where do the larger numbers appear on hydrometers, toward the bottom or toward the top of the stem? Explain.

7. A 150-lb. man can just float. What is his volume?

8. Describe fully how you would proceed to find the specific gravity of an irregular solid heavier than water, showing in every case why you proceed as you do.

9. A body loses 25 g. in water, 23 g. in oil, and 20 g. in alcohol. Find the specific gravity of the oil and of the alcohol.

* Laboratory experiments on the determination of the densities of solids and liquids should follow or accompany the discussion of this chapter. See, for example, Experiments 7 and 8 of the authors' Manual.

10. A platinum ball weighs 330 g. in air, 315 g. in water, and 303 g. in sulphuric acid. Find the volume of the ball and the specific gravity of the platinum and of the acid.

11. A piece of paraffin weighed 178 g. in air, and a sinker weighed 30 g. in water. Both together weighed 8 g. in water. Find the specific gravity of the paraffin.

12. A cube of iron 10 cm. on a side weighs 7500 g. What will it weigh in alcohol of density .82?

13. What fraction of the volume of a block of wood will float above water if its density is .5? if its density is .6? if its density is .9? State in general what fraction of the volume of a floating body is under water.

14. If a rectangular iceberg rises 100 ft. above water, how far does it extend below water? (Assume the density of the ice to be .9 that of sea water.)

15. A barge 30 ft. by 15 ft. sank 4 in. when an elephant was taken aboard. What was the elephant's weight?

16. A cubic foot of stone weighed 110 lb. in water. Find its specific gravity.

17. Steel is three times as heavy as aluminum. When equal volumes of each are submerged in water, how do their apparent losses of weight compare?

18. The density of cork is .25 g. per cubic centimeter. What force is required to push a cubic centimeter of cork beneath the surface of water?

19. A block of wood 15 cm. by 10 cm. by 4 cm. floats in water with 1 cm. in the air. Find the weight of the wood and its specific gravity.

20. The specific gravity of milk is 1.032. How is its specific gravity affected by removing part of the cream? by adding water? May these two changes be made so as not to alter its specific gravity at all?

21. A piece of sandstone having a specific gravity of 2.6 weighs 480 g. in water. Find its weight in air.

22. The density of stone is about 2.5. If a boy can lift 120 lb., how heavy a stone can he lift to the surface of a pond?

23. The hull of a modern battleship is made almost entirely of steel, its walls being of steel plates from 6 to 18 in. thick. Explain how it can float.

CHAPTER III

PRESSURE IN AIR

Barometric Phenomena

34. The weight of air. To ordinary observation air is scarcely perceptible. It appears to have no weight and to offer no resistance to bodies passing through it. But if a bulb is balanced as in Fig. 22, and then removed and filled with air under pressure by a few strokes of a bicycle pump, it will be found, when placed on the balance again, to be heavier than it was before. On the other hand, if the bulb is connected with an air pump and exhausted, it will be found to have lost weight.* Evidently, then, air can be put into and taken out of a vessel, weighed, and handled, just like a liquid or a solid.

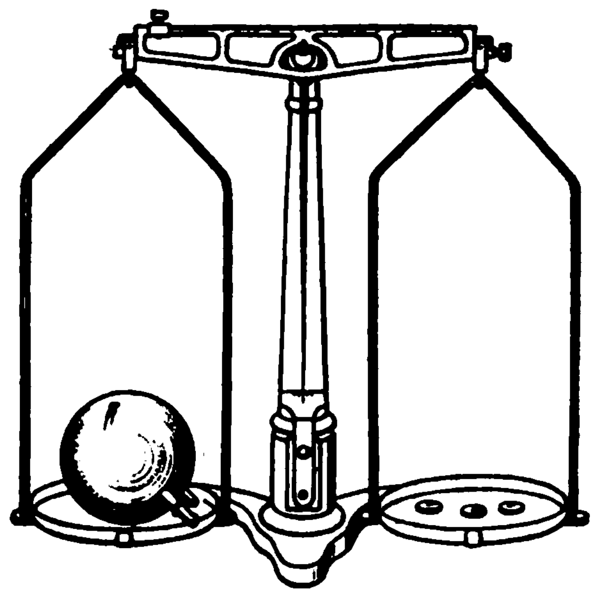


Fig. 22. Proof that air has weight

We are accustomed to say that bodies are "as light as air"; yet careful measurement shows that it takes but 12 cubic feet of air to weigh a pound, so that a single large room contains more air than an ordinary man can lift. Thus, the air in a room 60 feet by 30 feet by 15 feet weighs more than a ton. The exact weight of air at the freezing temperature and under normal atmospheric conditions is .001293 gram per cubic centimeter, that is, 1.293 grams per liter. A given volume of air therefore weighs $\frac{1}{773}$ as much as an equal volume of water.

* Another experiment is to weigh an electric-light bulb, then puncture it with a blowpipe and weigh again.

35. Proof that air exerts pressure. Since air has weight, it is to be inferred that air, like a liquid, exerts force against any surface immersed in it. The following experiments prove this.

Let a rubber membrane be stretched over a glass vessel, as in Fig. 23. As the air is exhausted from beneath the membrane the latter will be observed to be more and more depressed until it will finally burst under the pressure of the air above.

Again, let a tin can be partly filled with water and the water boiled. The air will be expelled by the escaping steam. While the boiling is

FIG. 23. Rubber membrane stretched by weight of air

FIG. 24. Gallon can crushed by atmospheric pressure

still going on, let the can be tightly corked, then placed in a sink or tray and cold water poured over it. The steam will be condensed and the weight of the air outside will crush the can (see Fig. 24).

36. Cause of the rise of liquids in exhausted tubes. If the lower end of a long tube be dipped into water and the air exhausted from the upper end, water will rise in the tube. We prove the truth of this statement every time we draw lemonade through a straw. The old Greeks and Romans explained such phenomena by saying that "nature abhors a vacuum," and this explanation was still in vogue in Galileo's time. But in 1640 the Duke of Tuscany had a deep well dug near Florence, and found to his surprise that no water pump which could be obtained would raise the water higher than about 32 feet above the level in the well. When he applied to the aged

Galileo (see opposite p. 72) for an explanation, the latter replied that evidently "nature's horror of a vacuum did not extend beyond 32 feet." It is quite likely that Galileo suspected that the pressure of the air was responsible for the phenomenon, for he had himself proved before that air had weight; and, furthermore, he at once devised another experiment to test, as he said, the "power of a vacuum." He died in 1642 before the experiment was performed, but suggested to his pupil Torricelli that he continue the investigation.

37. Torricelli's experiment. Torricelli argued that if water would rise 32 feet, then mercury, which is about 13 times as heavy as water, ought to rise but $\frac{1}{13}$ as high. To test this inference he performed, in 1643, the following famous experiment:

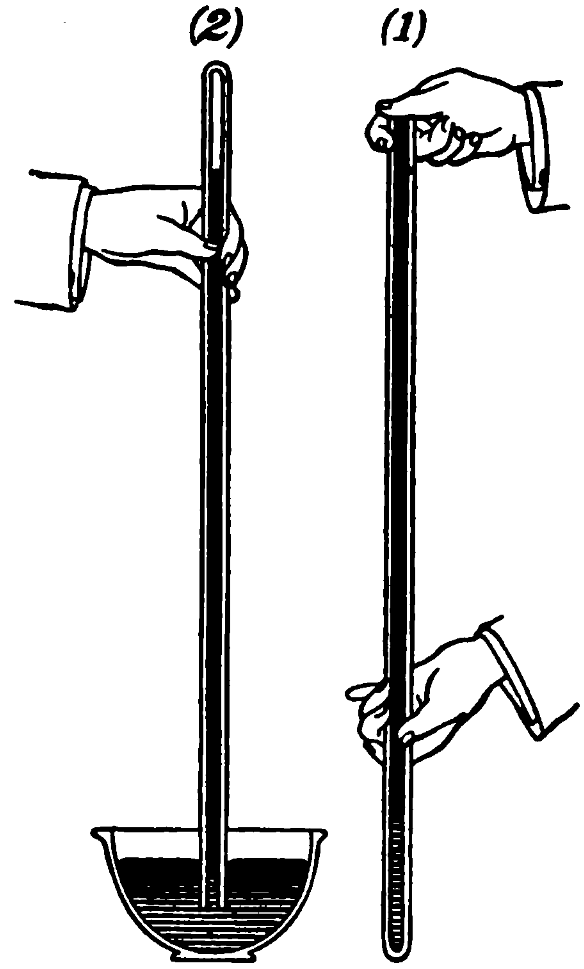


Fig. 25. Torricelli's experiment

Let a tube about 4 ft. long, which is sealed at one end, be completely filled with mercury, as in Fig. 25, (*1*), then closed with the thumb and inverted, and the bottom immersed in a dish of mercury, as in Fig. 25, (*2*). When the thumb is removed from the bottom of the tube, the mercury will fall away from the upper end of the tube, in spite of the fact that in so doing it will leave a vacuum above it; and its upper surface will, in fact, stand about $\frac{1}{13}$ of 32 ft., that is, between 29 and 30 in., above the mercury in the dish.

Torricelli concluded from this experiment that the rise of liquids in exhausted tubes is due to an outside pressure exerted by the atmosphere on the surface of the liquid, and not to any mysterious sucking power created by the vacuum as is popularly believed even to-day.

38. Further decisive tests. An unanswerable argument in favor of this conclusion will be furnished if the mercury in the tube falls as soon as the air is removed from above the surface of the mercury in the dish.

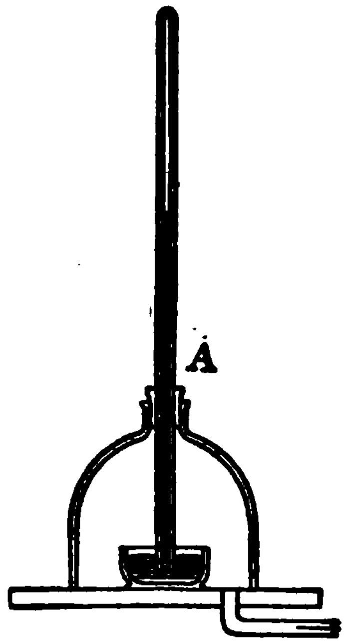


FIG. 26. Barometer falls when air pressure on the mercury surface is reduced

To test this point, let the dish and tube be placed on the table of an air pump, as in Fig. 26, the tube passing through a tightly fitting rubber stopper A in the bell jar. As soon as the pump is started the mercury in the tube will, in fact, be seen to fall. As the pumping is continued it will fall nearer and nearer to the level in the dish, although it will not usually reach it, for the reason that an ordinary vacuum pump is not capable of producing as good a vacuum as that which exists in the top of the tube. As the air is allowed to return to the bell jar the mercury will rise in the tube to its former level.

FIG. 27. Air column to top of atmosphere balances the mercury column *ab*

39. Amount of the atmospheric pressure. Torricelli's experiment shows exactly how great the atmospheric pressure is, since this pressure is able to balance a column of mercury of definite length. As the pressures along the same level *ac* (Fig. 27) are equal, the downward pressure exerted by the atmosphere on the surface of the mercury at c is equal to the downward pressure of the column of mercury at a. But the downward pressure at this point within the tube is equal to hd, where d is the density of mercury and h is the depth below the surface b. Since the average height of this

column at sea level is found to be 76 centimeters, and since the density of mercury is 13.6 grams per cubic centimeter, the downward pressure inside the tube at *a* is equal to 76 times 13.6 grams, or 1033.6 grams per square centimeter. Hence the atmospheric pressure acting on the surface of the mercury at *c* is 1033.6 grams, or, roughly, 1 kilogram per square centimeter. The pressure of one atmosphere is, then, about 15 pounds per square inch.

40. Pascal's experiment. Pascal thought of another way of testing whether or not it were indeed the weight of the outside air which sustains the column of mercury in an exhausted tube. He reasoned that, since the pressure in a liquid diminishes on ascending toward the surface, atmospheric pressure ought also to diminish on passing from sea level to a mountain top. As there was no mountain near Paris, he carried Torricelli's apparatus to the top of a high tower and found, indeed, a slight fall in the height of the column of mercury. He then wrote to his brother-in-law, Perrier, who lived near Puy de Dôme, a mountain in the south of France, and asked him to try the experiment on a larger scale. Perrier wrote back that he was "ravished with admiration and astonishment" when he found that on ascending 1000 meters the mercury sank about 8 centimeters in the tube. This was in 1648, five years after Torricelli's discovery.

At the present day geological parties actually ascertain differences in altitude by observing the change in the barometric pressure as they ascend or descend. A fall of 1 millimeter in the barometric height corresponds to an ascent of about 12 meters.

41. The barometer. The modern barometer (Fig. 28) is essentially nothing more nor less than Torricelli's tube. Taking a barometer reading consists simply in accurately measuring the height of the mercury column. This height varies from 73 to 76.5 centimeters in localities which are not far above

sea level, the reason being that disturbances in the atmosphere affect the pressure at the earth's surface in the same way in which eddies and high waves in a tank of water would affect the liquid pressure at the bottom of the tank.

The barometer does not directly foretell the weather, but it has been found that a low or rapidly falling pressure is usually accompanied, or soon followed, by stormy conditions. Hence the barometer, although not an infallible weather prophet, is nevertheless of considerable assistance in forecasting weather conditions some hours ahead. Further, by comparing at a central station the telegraphic reports of barometer readings made every few hours at stations all over the country, it is possible to determine in what direction the atmospheric eddies which cause barometer changes and stormy conditions are traveling and hence to forecast the weather even a day or two in advance.

42. The first barometers. Torricelli actually constructed a barometer not essentially different from that shown in Fig. 28 and used it for observing changes in the atmospheric pressure; but perhaps the most interesting of the early barometers was that set up about 1650 by Otto von Guericke of Magdeburg (1602–1686) (see opposite p. 32). He used for his barometer a water column the top of which passed through the roof of his house. A wooden image which floated on the upper surface of the water appeared above the housetop in fair weather but retired from sight in foul, a circumstance which led his neighbors to charge him with being in league with Satan.

FIG. 28. The Fortin barometer

43. The aneroid barometer. Since the mercurial barometer is somewhat long and inconvenient to carry, geological and surveying parties

commonly use an instrument called the *aneroid barometer.* It consists essentially of an air-tight cylindrical box the top of which is a metallic diaphragm which bends slightly under the influence of change in the atmospheric pressure. This motion of the top of the box is multiplied by a delicate system of levers and communicated to a hand which moves over a dial whose readings are made to correspond to the readings of a mercury barometer. These instruments are made so sensitive as to

Fig. 29. The aneroid barometer

indicate a change in pressure when they are moved no farther than from a table to the floor. In the self-recording aneroid barometer, or barograph, used by the United States Weather Bureau (Fig. 29), several of the air-tight boxes are superposed for greater sensitiveness, and the pressures are recorded in ink upon paper wound about a drum. Clockwork inside the drum makes it revolve once a week. A somewhat different form of the instrument is used by aviators to record altitude.

QUESTIONS AND PROBLEMS

1. Why does not the ink run out of a pneumatic inkstand like that shown in Fig. 30?

2. If a tumbler is filled, or partly filled, with water, and a piece of writing paper is placed over the top, it may be inverted, as in Fig. 31, without spilling the water. Explain. What is the function of the paper?

Otto von Guericke (1602–1686)

German physicist, astronomer, and man of affairs; mayor of Magdeburg, invented the air pump in 1650, and performed many new experiments with liquids and gases; discovered electrostatic repulsion; constructed the famous Magdeburg hemispheres which four teams of horses could not pull apart (see p. 38)

THE MERCURY-DIFFUSION AIR PUMP

The latest development of the air pump is shown in the accompanying diagram. It is over a million times more effective than an air pump of the mechanical kind invented by Von Guericke. The principle is as follows: The jet of water pouring out through J_1 from an ordinary water tap T entrains the air in the chamber C and thus pulls the pressure in C' down to from 10 to 15 mm. of mercury. Next, the mercury jet J_2, produced by boiling violently the mercury above the electric furnace F, entrains the air in the chamber C'' and thus lowers the pressure in this chamber to, say, .01 mm of mercury Again, the stream of mercury vapor pouring out of J_3, under the influence of the furnace F', carries with it the molecules of air coming out of C''' Finally, the liquid-air trap freezes out the mercury vapor, some of which would otherwise find its way through C''' into the high-vacuum chamber. So little air is finally left in this high-vacuum chamber that the pressure there may be as low as a hundred-millionth of a millimeter of mercury. Pumps of this sort are now used for exhausting audion bulbs and high-vacuum rectifiers, which are becoming of very great commercial value. The credit for the invention of this form of pump belongs primarily to a fellow countryman of Von Guericke, Professor Gaede, of Freiburg, Germany. Improvements of his design, however, have been made quite independently and along somewhat different lines by several Americans: namely, Irving Langmuir of the General Electric Company, Schenectady, O. E. Buckley of the Western Electric Company, New York; and W. W. Crawford of the Victor Electric Company, Chicago. The particular design shown in the diagram is due to Dr. J. E. Shrader of the Westinghouse Research Laboratory, Pittsburgh

3. If a small quantity of air should get into the space at the top of the mercury column of a barometer, how would it affect the readings? Why?

4. Would the pressure of the atmosphere hold mercury as high in a tube as large as your wrist as in one having the diameter of your finger? Explain.

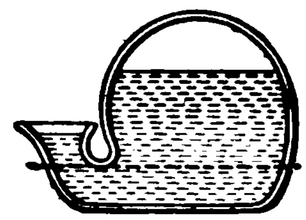


FIG. 30

5. Give three reasons why mercury is better than water for use in barometers.

6. Calculate the number of tons atmospheric force on the roof of an apartment house 50 ft. × 100 ft. Why does the roof not cave in?

7. Measure the dimensions of your classroom in feet and calculate the number of pounds of air in the room.

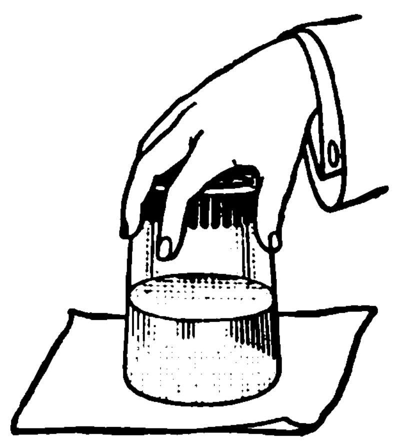


FIG. 31

8. Magdeburg hemispheres (Fig. 32) are so called because they were invented by Otto von Guericke, who was mayor of Magdeburg. When the lips of the hemispheres are placed in contact and the air exhausted from between them, it is found very difficult to pull them apart. Why?

9. Von Guericke's original hemispheres are still preserved in the museum at Berlin. Their interior diameter is 22 in. On the cover of the book which describes his experiments is a picture which represents four teams of horses on each side of the hemispheres, trying to separate them. The experiment was actually performed in this way before the German emperor Ferdinand III. If the air was all removed from the interior of the hemispheres, what force in pounds was in fact required to pull them apart? (Find the atmospheric force on a circle of 11 in. radius.)

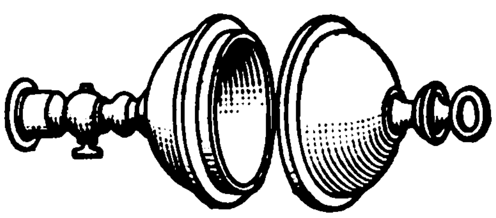


FIG. 32. Magdeburg hemispheres

COMPRESSIBILITY AND EXPANSIBILITY OF AIR

44. Incompressibility of liquids. Thus far we have found very striking resemblances between the conditions which exist at the bottom of a body of liquid and those which exist at the bottom of the great ocean of air in which we live. We now come to a most important difference. It is well known that if 2 liters of water be poured into a tall cylindrical vessel, the water will stand exactly twice as high as if the vessel contained

but 1 liter; or if 10 liters be poured in, the water will stand 10 times as high as if there were but 1 liter. This means that the lowest liter in the vessel is not measurably compressed by the weight of the water above it.

It has been found by carefully devised experiments that compressing weights enormously greater than these may be used without producing a marked effect; for example, when a cubic centimeter of water is subjected to the stupendous pressure of 3,000,000 grams, its volume is reduced to but .90 cubic centimeter. Hence we say that water, and liquids generally, are practically incompressible. Had it not been for this fact we should not have been justified in taking the pressure at any depth below the surface of the sea as the simple product of the depth by the density at the surface.

The depth bomb, so successful in the destruction of submarines, is effective because of the practical incompressibility of water. If the bomb explodes within a hundred feet of the submarine and is far enough down so that the force of the explosion is not lost through expansion at the surface, the effect is likely to be disastrous.

45. Compressibility of air. When we study the effects of pressure on air, we find a wholly different behavior from that described above for water. It is very easy to compress a body of air to one half, one fifth, or one tenth of its normal volume, as we prove every time we inflate a pneumatic tire or cushion of any sort. Further, the *expansibility* of air (that is, its tendency to spring back to a larger volume as soon as the pressure is relieved) is proved every time a tennis ball or a football bounds, or the air rushes out from a punctured tire.

But it is not only air which has been crowded into a pneumatic cushion by some sort of pressure pump which is in this state of readiness to expand as soon as the pressure is diminished; the ordinary air of the room will expand in the same way if the pressure to which it is subjected is relieved.

Thus, let a liter beaker with a sheet of rubber dam tied tightly over the top be placed under the receiver of an air pump. As soon as the pump is set into operation the inside air will expand with sufficient force to burst the rubber or greatly distend it, as shown in Fig. 33.

Again, let two bottles be arranged as in Fig. 34, one being stoppered air-tight, while the other is uncorked. As soon as the two are placed under the receiver of an air pump and the air exhausted, the water in *A* will pass over into *B*. When the air is readmitted to the receiver, the water will flow back. Explain.

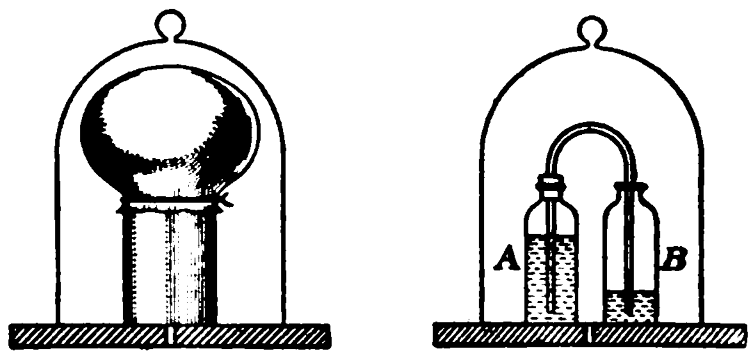


FIG. 33 FIG. 34

Illustrations of the expansibility of air

46. Why hollow bodies are not crushed by atmospheric pressure. The preceding experiments show why the walls of hollow bodies are not crushed in by the enormous forces which the weight of the atmosphere exerts against them. For the air inside such bodies presses their walls out with as much force as the outside air presses them in. In the experiment of § 35 the inside air was removed by the escaping steam. When this steam was condensed by the cold water, the inside pressure became very small and the outside pressure then crushed the can. In the experiment shown in Fig. 33 it was the outside pressure which was removed by the air pump, and the pressure of the inside air then burst the rubber.

47. Boyle's law. The first man to investigate the exact relation between the change in the pressure exerted by a confined body of gas and its change in volume was an Irishman, Robert Boyle (1627–1691). We shall repeat a modified form of his experiment much more carefully in the laboratory, but the following will illustrate the method by which he discovered one of the most important laws of physics, a law which is now known by his name.

Let mercury be poured into a bent glass tube until it stands at the same level in the closed arm AC as in the open arm BD (Fig. 35). There is now confined in AC a certain volume of air under the pressure of one atmosphere. Call this pressure P_1. Let the length AC be measured and called V_1. Then let mercury be poured into the long arm until the level in this arm is as many centimeters above the level in the short arm as there are centimeters in the barometer height. The confined air is now under a pressure of two atmospheres. Call it P_2. Let the new volume $A_1C(=V_2)$ be measured. It will be found to be just half its former value.

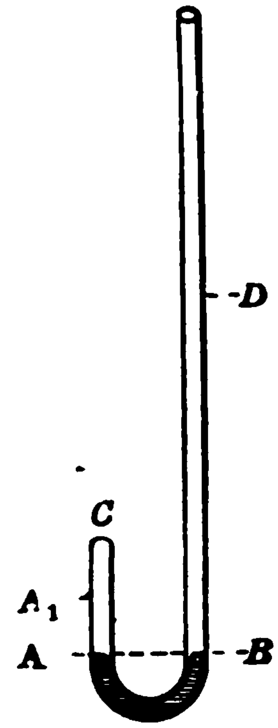


FIG. 35. Method of demonstrating Boyle's law

Hence we learn that doubling the pressure exerted upon a body of gas halves its volume. If we had tripled the pressure, we should have found the volume reduced to one third its initial value, etc. That is, *the pressure which a given quantity of gas at constant temperature exerts against the walls of the containing vessel is inversely proportional to the volume occupied.* This is algebraically stated thus:

$$\frac{P_1}{P_2}=\frac{V_2}{V_1}, \quad \text{or} \quad P_1V_1=P_2V_2. \tag{1}$$

This is Boyle's law. It may also be stated in slightly different form. Doubling, tripling, or quadrupling the pressure must double, triple, or quadruple the *density*, since the volume is made only one half, one third, or one fourth as much, while the mass remains unchanged. Hence *the pressure which a gas exerts is directly proportional to its density, or, algebraically,*

$$\frac{P_1}{P_2}=\frac{D_1}{D_2}.^* \tag{2}$$

48. Extent and character of the earth's atmosphere. From the facts of compressibility and expansibility of air we may

* A laboratory experiment on Boyle's law should follow this discussion. See, for example, Experiment 9 of the authors' Manual.

know that the air, unlike the sea, must become less and less dense as we ascend from the bottom toward the top. Thus, at the top of Mont Blanc, an altitude of about three miles, where the barometer height is but 38 centimeters, or one half of its value at sea level, the density also must, by Boyle's law, be just one half as much as at sea level.

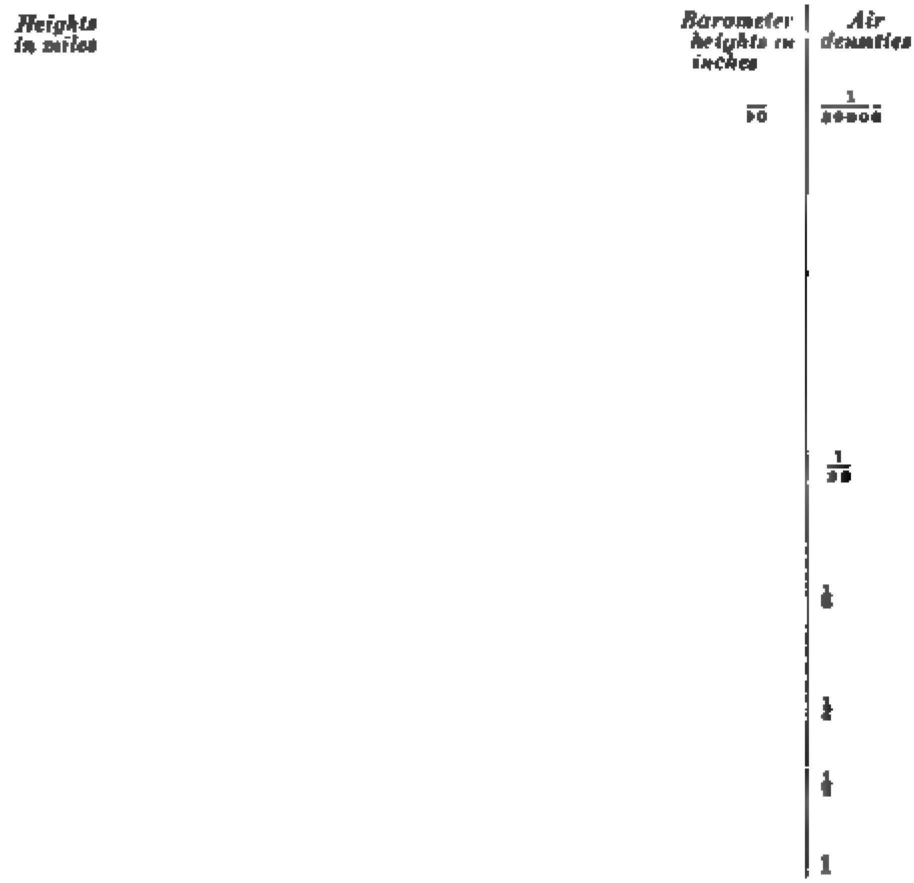


FIG. 36. Extent and character of atmosphere

No one has ever ascended higher than 7 miles, which was approximately the height attained in 1862 by the two daring English aëronauts Glaisher and Coxwell. At this altitude the barometric height is but about 7 inches, and the temperature about $-60°$ F. Both aëronauts lost the use of their limbs, and Mr. Glaisher became unconscious. Mr. Coxwell barely succeeded in grasping with his teeth the rope which opened a valve and caused the balloon to descend. Again, on July 31, 1901, the French aëronaut M. Berson rose without injury to

a height of about 7 miles (35,420 feet), his success being due to the artificial inhalation of oxygen. The American aviator Major R. W. Schroeder of the United States Army, on February 27, 1920, ascended in an airplane to a height of 33,000 feet. He found the temperature $-67°$ F.

By sending up self-registering thermometers and barometers in balloons which burst at great altitudes, the instruments being protected by parachutes from the dangers of rapid fall, the atmosphere has been explored to a height of 35,080 meters (21.8 miles), this being the height attained on December 7, 1911, by a little balloon which was sent up at Pavia, Italy. These extreme heights are calculated from the indications of the self-registering barometers.

At a height of 35 miles the density of the atmosphere is estimated to be but $\frac{1}{30000}$ of its value at sea level. By calculating how far below the horizon the sun must be when the last traces of color disappear from the sky, we find that at a height as great as 45 miles there must be air enough to reflect some light. How far beyond this an extremely rarified atmosphere may extend, no one knows. It has been estimated at all the way from 100 to 500 miles. These estimates are based on observations of the height at which meteors first become visible, on the height of the aurora borealis, and on the darkening of the surface of the moon just before it is eclipsed by the shadow of the solid earth.

QUESTIONS AND PROBLEMS

1. The deepest sounding in the ocean is about 6 mi. Find the pressure in tons per square inch at this depth. (Specific gravity of ocean water = 1.026.) Will a pebble thrown overboard reach the bottom? Explain.

2. What sort of a change in volume do the bubbles of air which escape from a diver's suit experience as they ascend to the surface?

3. With the aid of the experiment in which the rubber dam was burst under the exhausted receiver of an air pump explain why high

mountain climbing often causes pain and bleeding in the ears and nose. Why does deep diving produce similar effects?

4. Blow as hard as possible into the tube of the bottle shown in Fig. 37. Then withdraw the mouth and explain all of the effects observed.

5. If a bottle or cylinder is filled with water and inverted in a dish of water, with its mouth beneath the surface (see Fig. 38), the water will not run out. Why?

6. If a bent rubber tube is inserted beneath the cylinder and air blown in at *o* (Fig. 38), it will rise to the top and displace the water. This is the method regularly used in collecting gases. Explain what forces the gas up into it, and what causes the water to descend in the tube as the gas rises.

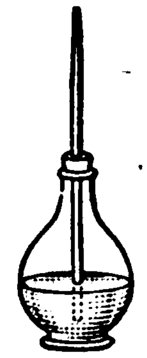


FIG. 37

7. Why must the bung be removed from a cider barrel in order to secure a proper flow from the faucet?

8. When a bottle full of water is inverted, the water will gurgle out instead of issuing in a steady stream. Why?

9. If 100 cu. ft. of hydrogen gas at normal pressure are forced into a steel tank having a capacity of 5 cu. ft., what is the gas pressure in pounds per square inch?

10. An automobile tire having a capacity of 1500 cu. in. is inflated to a pressure of 90 pounds per square inch. What is the density of the air within the tire? To what volume would the air expand if there should be a "blow-out"?

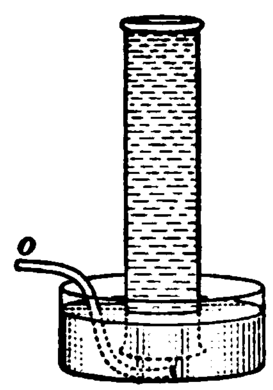


FIG. 38.

11. Under ordinary conditions a gram of air occupies about 800 cc. Find what volume a gram will occupy at the top of Mont Blanc (altitude 15,781 ft.), where the barometer indicates that the pressure is only about one half what it is at sea level.

12. The mean density of the air at sea level is about .0012. What is its density at the top of Mont Blanc? What fractional part of the earth's atmosphere has one left beneath him when he ascends to the top of this mountain?

13. If Glaisher and Coxwell rose in their balloon until the barometric height was only 18 cm., how many inhalations were they obliged to make in order to obtain the same amount of air which they could obtain at the surface in one inhalation?

14. 1 cc. of air at the earth's surface weighs .00129 g. If this were the density all the way up, to what height would the atmosphere extend?

Pneumatic Appliances

49. The siphon. Let a rubber or glass tube be filled with water and then placed in the position shown in Fig. 39. Water will be found to flow through the tube from vessel *A* into vessel *B*. If then *B* be raised until the water in it is at a higher level than that in *A*, the direction of flow will be reversed. This instrument, which is called the *siphon*, is very useful for removing liquids from vessels which cannot be overturned, or for drawing off the upper layers of a liquid without disturbing the lower layers. Many commercial applications of it are found in various siphon flushing systems.

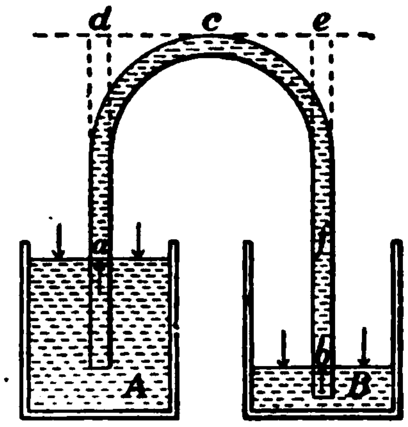


Fig. 39. The siphon

The explanation of the siphon's action is readily seen from Fig. 39. Since the tube *acb* is full of water, water must evidently flow through it if the force which pushes it one way is greater than that which pushes it the other way. Now the upward pressure at *a* is equal to atmospheric pressure minus the downward pressure due to the water column *ad*, while the upward pressure at *b* is the atmospheric pressure minus the downward pressure due to the water column *be*. Hence the pressure at *a* exceeds the pressure at *b* by the pressure due to the water column *fb*. The siphon will evidently cease to act when the water is at the same level in the two vessels, since then $fb = 0$ and the forces acting at the two ends of the tube are therefore equal and opposite. It will also cease to act when the bend *c* is more than 34 feet above the surface of the water in *A*, since then a vacuum will form at the top, atmospheric pressure being unable to raise water to a height greater than this in either tube.

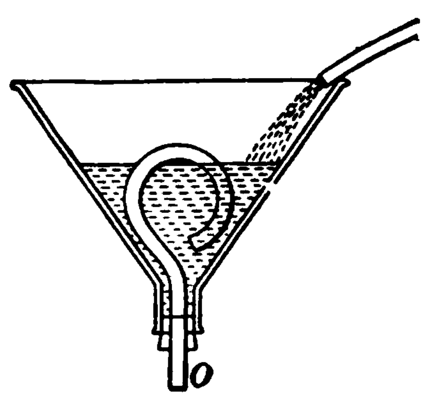


Fig. 40. Intermittent siphon

Would a siphon flow in a vacuum?

50. The intermittent siphon. Fig. 40 represents an intermittent siphon. If the vessel is at first empty, to what level must it be filled before the water will flow out at *o*? To what level will the water then fall before the flow will cease?

51. The air pump. The air pump was invented in 1650 by Otto von Guericke, mayor of Magdeburg, Germany, who deserves the greater credit since he was apparently altogether without knowledge of the discoveries which Galileo, Torricelli, and Pascal had made a few years earlier regarding the character of the earth's atmosphere. A simple form of such a pump is shown in Fig. 41. When the piston is raised, the air from the receiver *R* expands into the cylinder *B* through the valve *A*. When the piston descends, it compresses this air and thus closes the valve *A* and opens the exhaust valve *C*. Thus, with each double stroke a certain fraction of the air in the receiver is transferred from *R* through the cylinder to the outside.

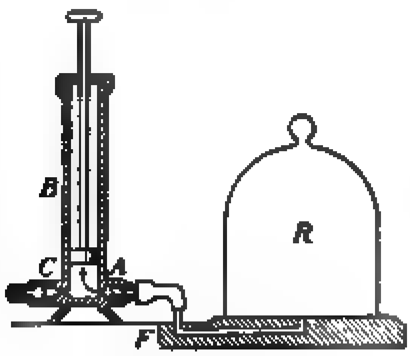


FIG. 41. A simple air pump

In many pumps the valve *C* is in the piston itself.

FIG. 42. Automobile compression pump

52. The compression pump. A compression pump is used for compressing a gas into a container. If the pump shown in Fig. 41 be detached from the receiver plate and the vessel to receive the gas be attached at *C*, we have a compression pump. Fig. 42 shows a common form of compression pump used for

inflating automobile tires. Cup valves are shown at *c* and *c'*. They are leather disks a little larger than the barrel of the pump, attached to a loosely fitting metal piston.

When the pistons are forced down, the valve *c* spreads tightly against the wall, forcing the air past the valves *c'* and *v*. On the upstroke the valve *c'* spreads and forces the compressed air in the small barrel past *v*, while at the same time air passes by *c*, again filling the two barrels. *v* prevents any air from reëntering the small barrel from the hose *h*. The greater compressing power of the two-barreled pump is due to the fact that *c'* on the upstroke compresses air that has already been compressed by *c* on the downstroke.

Compressed air finds so many applications in such machines as air drills (used in mining), air brakes, air motors, etc. that the compression pump must be looked upon as of much greater importance industrially than the exhaust pump.

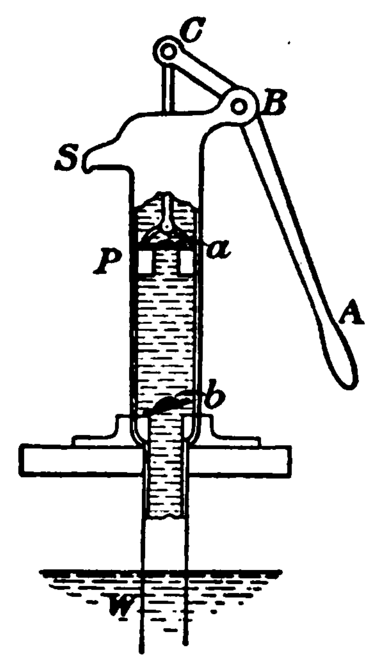


FIG. 43. The lift pump

53. The lift pump. The common water pump, shown in Fig. 43, has been in use at least since the time of Aristotle (fourth century B.C.). It will be seen from the figure that it is nothing more nor less than a simplified form of air pump. In fact, in the earlier strokes we are simply exhausting air from the pipe below the valve *b*. Water could never be obtained at *S*, even with a perfect pump, if the valve *b* were not within 34 feet of the surface of the water in *W*. Why? On account of mechanical imperfections this limit is usually about 28 feet instead of 34. Let the student analyze, stroke by stroke, the operation of pumping water from a well with the pump of Fig. 43. Why will pouring in a little water at the top, that is, "priming," often assist greatly in starting such a pump?

54. The force pump. Fig. 44 illustrates the construction of the force pump, a device commonly used when it is desired to deliver water at a point higher than the position at which it is convenient to place the pump itself. Let the student analyze the action of the pump from a study of the diagram.

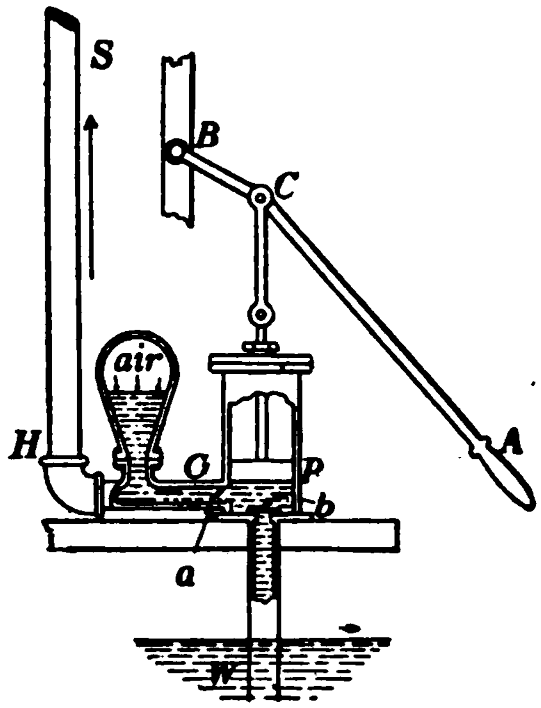


FIG. 44. The force pump

In order to make the flow of water in the pipe *HS* continue during the upstroke, an air chamber is always inserted between the valve *a* and the discharge point. As the water is forced violently into this chamber by the downward motion of the piston it compresses the confined air. It is, then, the reaction of this compressed air which is immediately responsible for the flow in the discharge tube; and as this reaction is continuous, the flow is also continuous.

55. The Cartesian diver. Descartes (1596–1650), the great French philosopher, invented an odd device which illustrates at the same time the principle of the transmission of pressure by liquids, the principle of Archimedes, and the compressibility of gases. A hollow glass image in human shape (Fig. 45, (1)) has an opening in the lower end. It is filled partly with water and partly with air, so that it will just float. By pressing on the rubber diaphragm at the top of the vessel it may be made to sink or rise at will. Explain. If the diver is not available, a small bottle or test tube (Fig. 45, (2)) may be used instead; it works equally well and brings out the principle even better.

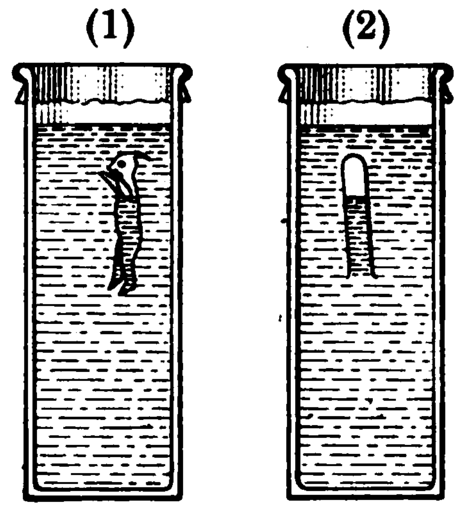


FIG. 45. The Cartesian diver

The modern submarine (see opposite page 23) is essentially nothing but a huge Cartesian diver which is propelled above water by oil or steam engines, and when submerged, by electric motors driven by storage batteries. The volume of the air in its chambers is changed by forcing water in or out, and it dives by a combined use of the propeller and horizontal rudders.

56. The balloon. A reference to the proof of Archimedes' principle (§ 29, p. 21) will show that it must apply as well to gases as to liquids. *Hence any body immersed in air is buoyed up by a force which is equal to the weight of the displaced air.* The body will therefore rise if its own weight is less than the weight of the air which it displaces.

A balloon is a large silk bag (see opposite page 45) impregnated with rubber and filled either with hydrogen or with common illuminating gas. The former gas weighs about .09 kilogram per cubic meter, and common illuminating gas weighs about .75 kilogram per cubic meter. It will be remembered that ordinary air weighs about 1.20 kilograms per cubic meter. It will be seen, therefore, that the lifting force of hydrogen per cubic meter namely, $1.20 - .09 = 1.11$, is more than twice the lifting force of illuminating gas, $1.20 - .75 = .45$.

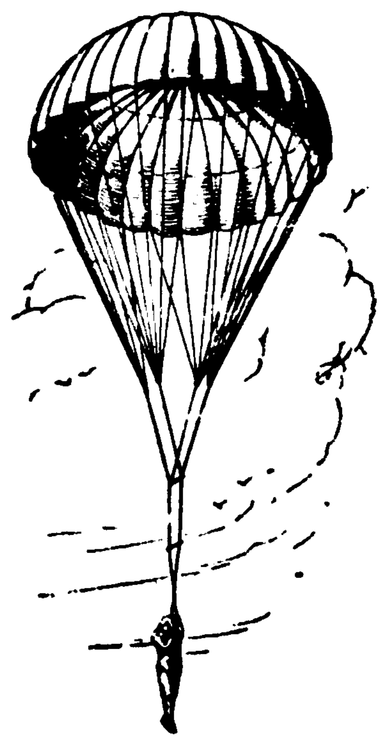


FIG. 46. The parachute

Ordinarily a balloon is not completely filled at the start; for if it were, since the outside pressure is continually diminishing as it ascends, the pressure of the inside gas would subject the bag to enormous strain and would surely burst it before it reached any considerable altitude. But if it is but partially inflated at the start, it can increase in volume as it ascends by simply inflating to a greater extent. Thus, a balloon which ascends until the pressure is but 7 centimeters of mercury should be only about one fourth inflated when it is at the surface.

The parachute (Fig. 46) is a huge, umbrella-like affair with which the aëronaut may descend in safety to the earth. After opening, it descends very slowly on account of the enormous surface exposed to the air. A hole in the top allows air to escape slowly, and thus keeps the parachute upright.

© Central News Photo Service

MONSTER BRITISH DIRIGIBLE AIRSHIP *R-34* ARRIVING IN AMERICA

The *R-34* photogra er gondola touched the ground at Mineola, after the first trans-atlantic flight of a r machine. This was the longest air flight nautical miles, from Scotland to New York, in exactly 4½ days, or 108 hours. On account of severe weather conditions and route taken the actual distance covered was 6300 nautical miles. She returned to Scotland in 75 hours. The characteristics of this historic airship are length, 672 ft.; height, 90 ft.; diameter, 79 ft.; 5 engines, 250 to 275 H.P. each (normal r.p.m. = 1600); total H.P., 1250 to 1375; 19 gas bags of goldbeater's skin (calf's intestine); capacity, 2,000,000 cu. ft.; each engine, 12 cylinders; propellers geared to ½ engine speed; frame made of duralumin (= 95% Al); catwalk inside envelope, 600 ft.; total weight, 59 gross tons, of which 16 tons is gasoline (= 4900 gal.); can rise to a height of 14,000 ft.

© U. S. Official

THE UNITED STATES ARMY OBSERVATION BALLOON

The United States army observation balloon, commonly called a kite balloon, has a length of 90 ft., a diameter of 29 ft., and a capacity of 37,000 cu. ft. It is allowed to rise to various heights from anchorage to the earth, and observations are communicated to earth by telephone. The close-up view shows an American major of the balloon service in the basket of a balloon near the front-line trenches in France, June, 1918. In case of very sudden attack by enemy airplanes the observer escapes by means of the parachute seen hanging from the side of the basket

57. Helium balloons. One of the striking results of the World War was the development of the helium balloon. Helium is a noninflammable gas twice as dense as hydrogen and having a lifting power .92 as great. It is so rare an element that before the war not over 100 cu. ft. had been collected by anyone. Its pre-war price was $1700 per cu. ft. At the close of the war 147,000 cu. ft., extracted at a cost of ten cents a cubic foot from the gas wells of Texas and Oklahoma, were ready for shipment to France, and plans were under way for producing it at the rate of 50,000 cu. ft. per day.* The production of a balloon gas that assures safety from fire opens up a new era for the dirigible balloon (see opposite page 44).

A

Fig. 47. The diving bell

58. The diving bell. The diving bell (Fig. 47) is a heavy, bell-shaped body with rigid walls, which sinks of its own weight. Formerly the workmen who went down in the bell had at their disposal only the amount of air confined within it, and the water rose to a certain height within the bell on account of the compression of the air. But in modern practice the air is forced in from the surface through a connecting tube *a* (Fig. 48) by means of a force pump *h*. This arrangement, in addition to furnishing a continual supply of fresh air, makes it possible to force the water down to the level of the bottom of the bell. In practice a continual stream of bubbles is kept flowing out from the lower edge of the bell, as shown in Fig. 48, which illustrates subaqueous construction.

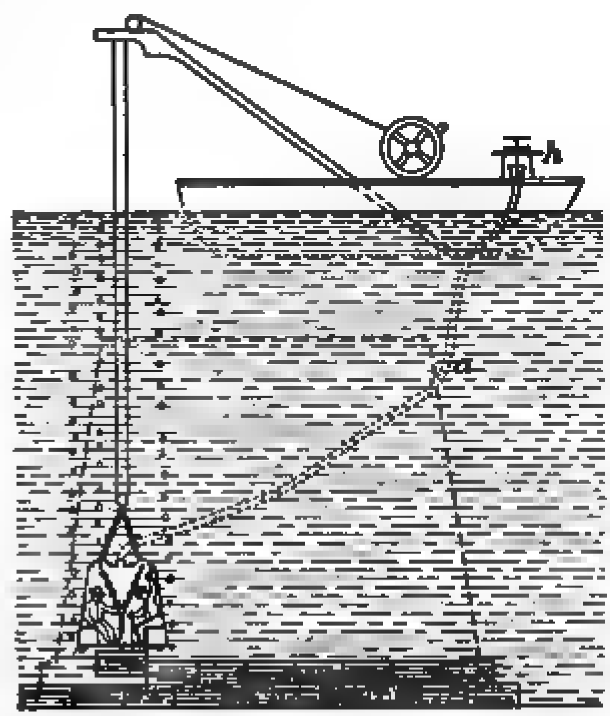


Fig. 48. Laying foundations of piers with the diving bell

The pressure of the air within the bell must, of course, be the pressure existing within the water at the depth of the level of the water inside the bell; that is, in Fig. 47 at the depth *AC*. Thus, at a depth of 34 feet the pressure is 2 atmospheres. Diving bells are used for putting in the foundations of bridge piers, doing subaqueous excavating, etc. The so-called *caisson*, much used in bridge building, is simply a huge stationary diving bell, which the workmen enter through compartments provided with air-tight doors. Air is pumped into it precisely as in Fig. 48.

59. The diving suit. For most purposes except those of heavy engineering the diving suit (Fig. 49) has now replaced the diving bell. This suit is made of rubber and has a metal helmet. The diver is sometimes connected with the surface by a tube through which air is forced down to him. It passes out into the water through the valve *V* in his suit. But more commonly the diver is entirely independent of the surface, carrying air under a pressure of about 40 atmospheres in a tank on his back. This air is allowed to escape gradually through the suit and out into the water through the valve *V* as fast as the diver needs it. When he wishes to rise to the surface, he simply admits enough air to his suit to make him float.

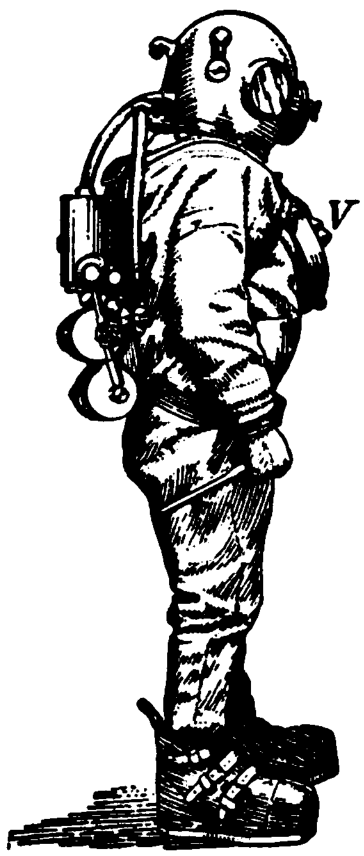


FIG. 49. The diving suit

In all cases the diver is subjected to the pressure existing at the depth at which the suit or bell communicates with the outside water. Divers seldom work at depths greater than 60 feet, and 80 feet is usually considered the limit of safety. But Chief Gunner's Mate Frank Crilley, investigating the sunken U. S. submarine *F-4* at Honolulu in 1915, descended to a depth of 304 feet.

The diver experiences pain in the ears and above the eyes when he is ascending or descending, but not when at rest. This is because it requires some time for the air to penetrate into the interior cavities of the body and establish equal pressure in both directions.

60. The gas meter. Gas from the city supply enters the meter through *P* (Fig. 50) and passes through the openings *o* and o_1 into the compartments *B* and B_1 of the meter. Here its pressure forces in the diaphragms

d and d_1. The gas already contained in A and A_1 is therefore pushed out to the burners through the openings o' and o'_1 and the pipe P_1. As soon as the diaphragm d has moved as far as it can to the right, a lever which is worked by the movement of d causes the slide valve u to move to the left, thus closing o and shutting off connection between P and B, but at the same time opening o' and allowing the gas from P to enter compartment A through o'. A quarter of a cycle later u_1 moves to the right and connects A_1 with P and B_1 with P_1. If u and u_1 were set so as to work exactly together, there would be slight fluctuations in the gas pressure at P_1. The movement of the diaphragms is recorded by a clockwork device, the dials of which indicate the number of cubic feet of gas which have passed through the meter.

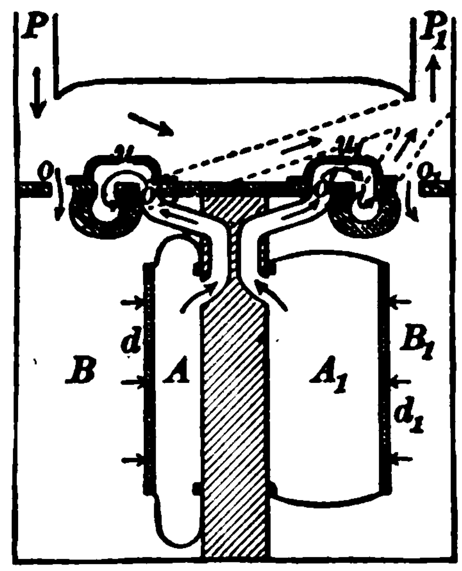


FIG. 50. The gas meter

QUESTIONS AND PROBLEMS

1. A water tank 8 ft. deep, standing some distance above the ground, closed everywhere except at the top, is to be emptied. The only means of emptying it is a flexible tube. (a) What is the most convenient way of using the tube, and how could it be set into operation? (b) How long must the tube be to empty the tank completely?

2. Kerosene has a specific gravity of .8. Over what height can it be siphoned at normal pressure?

3. Let a siphon of the form shown in Fig. 51 be made by filling a flask one third full of water, closing it with a cork through which pass two pieces of glass tubing, as in the figure, and then inverting so that the lower end of the straight tube is in a dish of water. If the bent arm is of considerable length, the fountain will play forcibly and continuously until the dish is emptied. Explain.

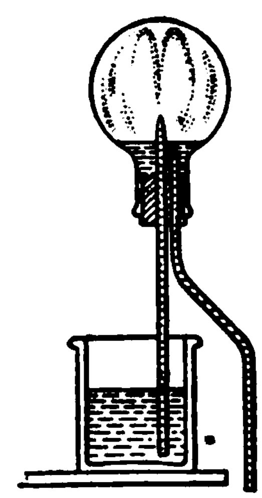


FIG. 51

4. Diagram a lift pump on upstroke. What causes the water to rise in the suction pipe? What happens on downstroke?

5. Diagram a force pump with air dome on downstroke. What happens on upstroke?

6. If the cylinder of an air pump is of the same size as the receiver, what fractional part of the air is removed by one complete stroke? What fractional part is left after 3 strokes? after 10 strokes?

7. If the cylinder of an air pump is one third the size of the receiver, what fractional part of the original air will be left after 5 strokes? What will be the reading of a barometer within the receiver, the outside pressure being 76?

8. Theoretically, can a vessel ever be completely exhausted by an air pump, even if mechanically perfect?

9. Explain by reference to atmospheric pressure why a balloon rises.

10. How many of the laws of liquids and gases do you find illustrated in the experiment of the Cartesian diver?

11. Pneumatic dispatch tubes are now used in many large stores for the transmission of small packages. An exhaust pump is attached to one end of the tube in which a tightly fitting carriage moves, and a compression pump to the other. If the air is half exhausted on one side of the carriage and has twice its normal density on the other, find the propelling force acting on the carriage when the area of its cross section is 50 sq. cm.

12. What determines how far a balloon will ascend? Under what conditions will it begin to descend? Explain these phenomena by the principle of Archimedes.

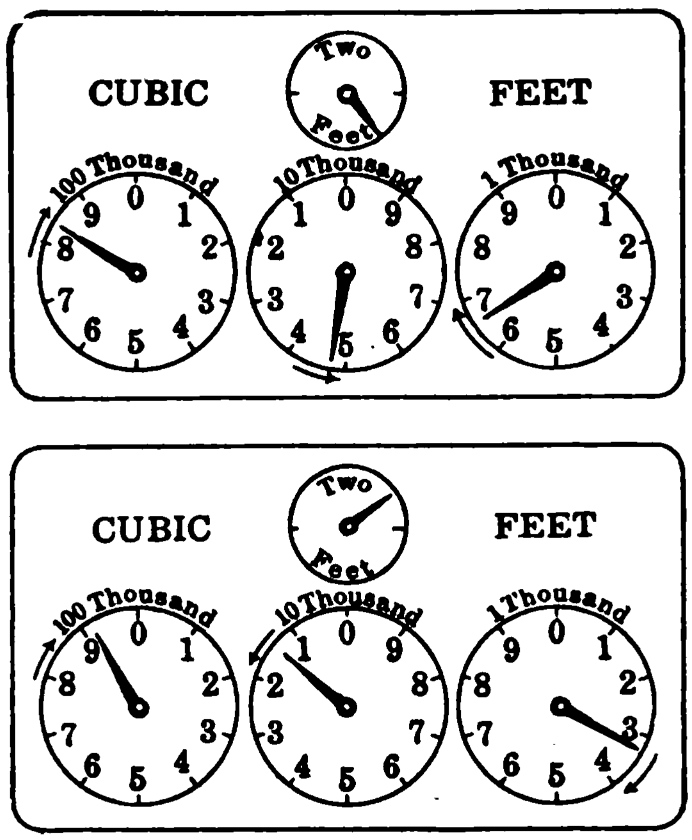


FIG. 52. The dials of a gas meter

13. If a diving bell (Fig. 47) is sunk until the level of the water within it is 1033 cm. beneath the surface, to what fraction of its initial volume has the inclosed air been reduced? (1033 g. per sq. cm. = 1 atmosphere.)

14. If a diver's tank has a volume of 2 cu. ft. and contains air under a pressure of 40 atmospheres, to what volume will the air expand when it is released at a depth of 34 ft. under water?

15. A submarine weighs 1800 tons when its submerging tanks are empty, and in that condition 10 per cent by volume of the submarine is above water. What weight of water must be let into the tanks to just submerge the boat?

16. (a) The upper figure shows a reading of 84,600 cu. ft. of gas. The lower figure shows the reading of the meter a month later. What was the amount of the bill for the month at \$.80 per 1000 cu. ft.? (b) Diagram the meter dials to represent 49,200 cu. ft.

CHAPTER IV

MOLECULAR MOTIONS

Kinetic Theory of Gases

61. Molecular constitution of matter. In order to account for some of the simplest facts in nature — for example, the fact that two substances often apparently occupy the same space at the same time, as when two gases are crowded together in the same vessel or when sugar is dissolved in water — it is now universally assumed that all substances are composed of very minute particles called *molecules*. Spaces are supposed to exist between these molecules, so that when one gas enters a vessel which is already full of another gas the molecules of the one scatter themselves about among the molecules of the other. Since molecules cannot be seen with the most powerful microscopes, it is evident that they must be very minute. The number of them contained in a cubic centimeter of air is 27 billion billion (27×10^{18}). It would take as many as a thousand molecules laid side by side to make a speck long enough to be seen with the best microscopes.

62. Evidence for molecular motions in gases. Certain very simple observations lead us to the conclusion that the molecules of gases, even in a still room, must be in continual and quite rapid motion. Thus, if a little chlorine, or ammonia, or any gas of powerful odor is introduced into a room, in a very short time it will have become perceptible in all parts of the room. This shows clearly that enough of the molecules of the gas to affect the olfactory nerves must have found their way across the room.

Again, chemists tell us that if two globes, one containing hydrogen and the other carbon dioxide gas, be connected as in Fig. 53, and the stopcock between them opened, after a few hours chemical analysis will show that each of the globes contains the two gases in exactly the same proportions, — a result which is at first sight very surprising, since carbon dioxide gas is about twenty-two times as heavy as hydrogen. This mixing of gases in apparent violation of the laws of weight is called *diffusion.*

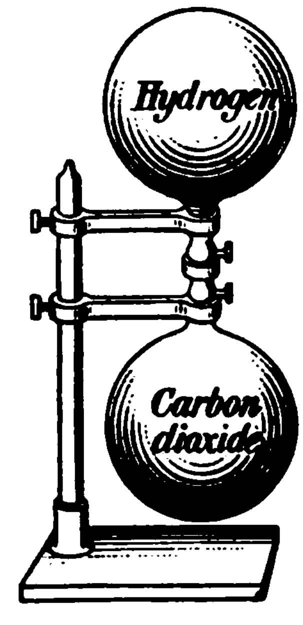


FIG. 53. Illustrating the diffusion of gases

We see, then, that such simple facts as the transference of odors and the diffusion of gases furnish very convincing evidence that the molecules of a gas are not at rest but are continually moving about.

63. Molecular motions and the indefinite expansibility of a gas. Perhaps the most striking property which we have found gases to possess is the property of indefinite or unlimited expansibility. The existence of this property was demonstrated by the fact that we were able to attain a high degree of exhaustion by means of an air pump. No matter how much air was removed from the bell jar, the remainder at once expanded and filled the entire vessel. The motions of the molecules furnish a thoroughly satisfactory explanation of the phenomenon.

The fact that, however rapidly the piston of the air pump is drawn up, gas always appears to follow it instantly, leads us to the conclusion that the natural velocity possessed by the molecules of gas must be very great.

64. Molecular motions and gas pressures. How are we to account for the fact that gases exert such pressures as they do against the walls of the vessels which contain them? We have found that in an ordinary room the air presses against the walls with a force of 15 pounds to the square

inch. Within an automobile tire this pressure may amount to as much as 100 pounds, and the steam pressure within the boiler of an engine is often as high as 240 pounds per square inch. Yet in all these cases we may be certain that the molecules of the gas are separated from each other by distances which are large in comparison with the diameters of the molecules; for when we reduce steam to water, it shrinks to $\frac{1}{1600}$ of its original volume, and when we reduce air to the liquid form, it shrinks to about $\frac{1}{800}$ of its ordinary volume.

The explanation is at once apparent when we reflect upon the *motions* of the molecules. For just as a stream of water particles from a hose exerts a continuous force against a wall on which it strikes, so the blows which the innumerable molecules of a gas strike against the walls of the containing vessel must constitute a continuous force tending to push out these walls. In this way we account for the fact that vessels containing only gas do not collapse under the enormous external pressures to which we know them to be subjected. A soap bubble $6\frac{1}{2}$ inches in diameter is, at normal atmospheric pressure, under a total crushing force of one ton.

65. Explanation of Boyle's law. It will be remembered that it was discovered in the last chapter that when the density of a gas is doubled, the temperature remaining constant, the pressure is found to double also; when the density was trebled, the pressure was trebled; etc. This, in fact, was the assertion of Boyle's law. Now this is exactly what would be expected if the pressure which a gas exerts against a given surface is due to blows struck by an enormous number of swiftly moving molecules; for doubling the number of molecules in the given space, that is, doubling the density, would simply double the number of blows struck per second against that surface, and hence would double the pressure. The kinetic theory of gases which is here presented accounts in this simple way for Boyle's law.

66. Brownian movements and molecular motions. It has recently been found possible to demonstrate the existence of molecular motions in gases in a very direct and striking way. It is found that very minute oil drops suspended in perfectly stagnant air, instead of being themselves at rest, are ceaselessly dancing about just as though they were endowed with life. In 1913 it was definitely proved that these motions, which are known as the *Brownian movements,* are the direct result of the bombardment which the droplets receive from the flying molecules of the gas with which they are surrounded; for at a given instant this bombardment is not the same on all sides, and hence the suspended particle, if it is minute enough, is pushed hither and thither according as the bombardment is more intense first in one direction, then in another. There can be no doubt that what the oil drops are here seen to be doing, the molecules themselves are also doing, only in a much more lively way.

67. Molecular velocities. From the known weight of a cubic centimeter of air under normal conditions, and the known force which it exerts per square centimeter (namely, 1033 grams), it is possible to calculate the velocity which its molecules must possess in order that they may produce by their collisions against the walls this amount of force. The result of the calculation gives to the air molecules under normal conditions a velocity of about 445 meters per second, while it assigns to the hydrogen molecules the enormous speed of 1700 meters (a mile) per second. The speed of a projectile is seldom greater than 800 meters (2500 feet) per second. It is easy to see, then, since the molecules of gases are endowed with such speeds, why air, for example, expands instantly into the space left behind by the rising piston of the air pump, and why any gas always fills completely the vessel which contains it (see mercury-diffusion air pump, opposite page 33).

68. Diffusion of gases through porous walls. Strong evidence for the correctness of the above views is furnished by the following experiment:

Let a porous cup of unglazed earthenware be closed with a rubber stopper through which a glass tube passes, as in Fig. 54. Let the tube be dipped into a dish of colored water, and a jar containing hydrogen placed over the porous cup; or let the jar simply be held in the position shown in the figure, and let illuminating gas be passed into it by means of a rubber tube connected with a gas jet. The rapid passage of bubbles out through the water will show that the gaseous pressure inside the

cup is rapidly increasing. Now let the bell jar be lifted, so that the hydrogen is removed from the outside. Water will at once begin to rise in the tube, showing that the inside pressure is now rapidly decreasing.

The explanation is as follows: We have learned that the molecules of hydrogen have about four times the velocity of the molecules of air. Hence, if there are as many hydrogen molecules per cubic centimeter outside the cup as there are air molecules per cubic centimeter inside, the hydrogen molecules will strike the outside of the wall four times as frequently as the air molecules will strike the inside. Hence, in a given time the number of hydrogen molecules which pass into the interior of the cup through the little holes in the porous material is four times as great as the number of air particles which pass out; hence the pressure within increases. When the bell jar is removed, the hydrogen which has passed inside begins to pass out faster than the outside air passes in, and hence the inside pressure is diminished.

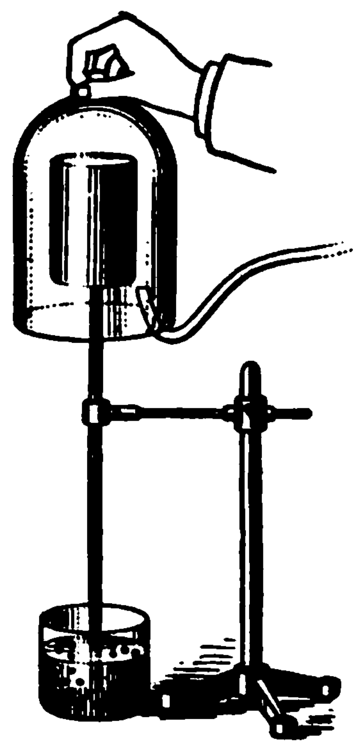


FIG. 54. Diffusion of hydrogen through porous cup

MOLECULAR MOTIONS IN LIQUIDS

69. Molecular motions in liquids and evaporation. Evidence that the molecules of liquids as well as those of gases are in a state of perpetual motion is found, first, in the familiar facts of evaporation.

We know that the molecules of a liquid in an open vessel are continually passing off into the space above, for it is only a matter of time when the liquid completely disappears and the vessel becomes dry. Now it is hard to imagine a way in which the molecules of a liquid thus pass out of the liquid into the space above, unless these molecules, while in the liquid condition,

are in motion. As soon, however, as such a motion is assumed, the facts of evaporation become perfectly intelligible. For it is to be expected that in the jostlings and collisions of rapidly moving liquid molecules an occasional molecule will acquire a velocity much greater than the average. This molecule may then, because of the unusual speed of its motion, break away from the attraction of its neighbors and fly off into the space above. This is indeed the mechanism by which we now believe that the process of evaporation goes on from the surface of any liquid.

70. Molecular motions and the diffusion of liquids. One of the most convincing arguments for the motions of molecules in gases was found in the fact of diffusion. But precisely the same sort of phenomena are observable in liquids.

Let a few lumps of blue litmus be pulverized and dissolved in water. Let a tall glass cylinder be half filled with this water and a few drops of ammonia added. Let the remainder of the litmus solution be turned red by the addition of one or two cubic centimeters of nitric acid. Then let this acidulated water be introduced into the bottom of the jar through a thistle tube (Fig. 55). In a few minutes the line of separation between the acidulated water and the blue solution will be fairly sharp; but in the course of a few hours, even though the jar is kept perfectly quiet, the red color will be found to have spread considerably toward the top, showing that the acid molecules have gradually found their way up.

FIG. 55. Diffusion of liquids

Certainly, then, the molecules of a liquid must be endowed with the power of independent motion. Indeed, every one of the arguments for molecular motions in gases applies with equal force to liquids. Even the Brownian movements can be seen in liquids, though they are here so small that high-power microscopes must be used to make them apparent.

Molecular Motions in Solids

71. Molecular motions and the diffusion of solids. It has recently been demonstrated that if a layer of lead is placed upon a layer of gold, molecules of gold may in time be detected throughout the whole mass of the lead. This diffusion of solids into one another at ordinary temperature has been shown only for these two metals, but at higher temperatures (for example, 500° C.) all of the metals show the same characteristics to quite a surprising degree.

The evidence for the existence of molecular motions in solids is, then, no less strong than in the case of liquids.

72. The three states of matter. Although it has been shown that, in accordance with current belief, the molecules of all substances are in very rapid motion, yet differences exist in the kind of motion which the molecules in the three states possess. Thus, in the solid state it is probable that the molecules oscillate with great rapidity about certain fixed points, always being held by the attractions of their neighbors, that is, by the *cohesive forces* (see § 112), in very nearly the same positions with reference to other molecules in the body. In rare instances, however, as the facts of diffusion show, a molecule breaks away from its constraints. In liquids, on the other hand, while the molecules are, in general, as close together as in solids, they slip about with perfect ease over one another and thus have no fixed positions. This assumption is necessitated by the fact that liquids adjust themselves readily to the shape of the containing vessel. In gases the molecules are comparatively far apart, as is evident from the fact that a cubic centimeter of water occupies about 1600 cubic centimeters when it is transformed into steam; and, furthermore, they exert almost no cohesive force upon one another, as is shown by the indefinite expansibility of gases.

QUESTIONS AND PROBLEMS

1. If a vessel with a small leak is filled with hydrogen at a pressure of 2 atmospheres, the pressure falls to 1 atmosphere about four times as fast as when the same experiment is tried with air. Can you see a reason for this?

2. What is the density of the air within an automobile tire that is inflated to a pressure of 80 lb. per square inch? (1 atmosphere = 14.7 lb. per sq. in.)

3. A liter of air at a pressure of 76 cm. is compressed so as to occupy 400 cc. What is the pressure against the walls of the containing vessel?

4. If an open vessel contains 250 g. of air when the barometric height is 750 mm., what weight will the same vessel contain at the same temperature when the barometric height is 740 mm.?

5. Find the pressure to which the diver was subjected who descended to a depth of 304 ft. Find the density of the air in his suit, the density at the surface being .00128 g. per cubic centimeter and the temperature being assumed to remain constant. Take the pressure at the surface as 30 in.

6. A bubble of air which escaped from this diver's suit would increase to how many times its volume on reaching the surface?

7. Salt is heavier than water. Why does not all the salt in a mixture of salt and water settle to the bottom?

CHAPTER V

FORCE AND MOTION

Definition and Measurement of Force

73. Distinction between a gram of mass and a gram of force. If a gram of mass is held in the outstretched hand, a downward pull upon the hand is felt. If the mass is 50,000 g. instead of 1, this pull is so great that the hand cannot be held in place. The cause of this pull we assume to be an attractive force which the earth exerts on the matter held in the hand, and *we define the gram of force as the amount of the earth's pull at its surface upon one gram of mass.*

Unfortunately, in ordinary conversation we often fail altogether to distinguish between the idea of mass and the idea of force, and use the same word "gram" to mean sometimes *a certain amount of matter* and at other times *the pull of the earth upon this amount of matter.* That the two ideas are, however, wholly distinct is evident from the consideration that the amount of matter in a body is always the same, no matter where the body is in the universe, while the pull of the earth upon that amount of matter decreases as we recede from the earth's surface. It will help to avoid confusion if we reserve the simple term "gram" to denote exclusively an amount of matter (that is, a mass) and use the full expression "gram of force" wherever we have in mind the pull of the earth upon this mass.

74. Method of measuring forces. When we wish to compare accurately the pulls exerted by the earth upon different masses, we find such sensations as those described in the

preceding paragraph very untrustworthy guides. An accurate method, however, of comparing these pulls is that furnished by the stretch produced in a spiral spring. Thus, the pull of the earth upon a gram of mass at its surface will stretch a given spring a given distance, *ab* (Fig. 56); the pull of the earth upon 2 grams of mass is found to stretch the spring a larger distance, *ac*; upon 3 grams, a still larger distance, *ad*; etc. In order to graduate a spring balance (Fig. 57) so that it will thenceforth measure the values of any pulls exerted upon it, no matter how these pulls may arise, we have only to place a fixed surface behind the pointer and make lines upon it corresponding to the points to which it is stretched by the pull of the earth upon different masses.

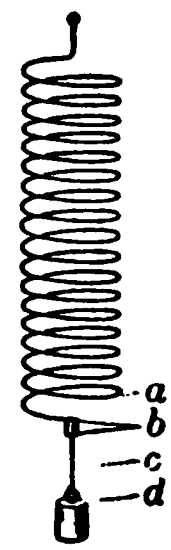


FIG. 56. Method of measuring forces

Thus, if a man stretch the spring so that the pointer is opposite the mark corresponding to the pull of the earth upon 2 grams of mass, we say that he exerts 2 grams of force; if he stretch it the distance corresponding to the pull of the earth upon 3 grams of mass, he exerts 3 grams of force; etc. The spring balance thus becomes an instrument for measuring forces.

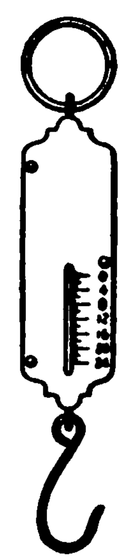


FIG. 57. The spring balance

75. The gram of force varies slightly in different localities. With the spring balance it is easy to verify the statement made above, that the force of the earth's pull decreases as we recede from the earth's surface; for upon a high mountain the stretch produced by a given mass is indeed found to be slightly less than at sea level. Furthermore, if the balance is simply carried from point to point over the earth's surface, the stretch is still found to vary slightly. For example, at Chicago it is about one part in 1000 less than it

is at Paris, and near the equator it is five parts in 1000 less than it is near the pole. This is due in part to the earth's rotation and in part to the fact that the earth is not a perfect sphere and that in going from the equator toward the pole we are coming nearer and nearer to the center of the earth. We see, therefore, that *the weight of one gram of mass is not an absolutely definite unit of force.* One gram of force is, strictly speaking, the weight of one gram of mass in latitude 45° at sea level.

Composition and Resolution of Forces

76. Graphic representation of force. A force is completely described when its *magnitude*, its *direction*, and the *point at which it is applied* are given. Since the three characteristics of a straight line are its *length*, its *direction*, and the *point at which it starts*, it is obviously possible to represent forces by means of straight lines. Thus, if we wish to represent the fact that a force of 8 pounds, acting in an easterly direction, is applied at the point A (Fig. 58), we draw a line 8 units long, beginning at the point A and extending to the right. The length of this line then represents the magnitude of the force; the direction of the line, the direction of the force; and the starting point of the line, the point at which the force is applied.

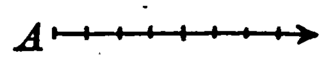


FIG. 58. Graphic representation of a single force

77. Resultant of two forces acting in the same line. *The resultant of two forces is defined as that single force which will produce the same effect upon a body as is produced by the joint action of the two forces.*

If two spring balances are attached to a small ring and pulled in the same direction until one registers 10 g. of force and the other 5, it will be found that a third spring balance attached to the same point and pulled in the opposite direction will register exactly 15 g. when there is equilibrium;

that is, *the resultant of two parallel forces acting in the same direction is equal to the sum of the two forces.*

Similarly, *the resultant of two oppositely directed forces applied at the same point is equal to the difference between them, and its direction is that of the greater force.*

78. Equilibrant. In the last experiment the pull in the spring balance which registered 15 g. was not the resultant of the 5 g. and 10 g. forces; it was rather a force equal and opposite to that resultant. Such a force is called an *equilibrant. The equilibrant of a force or forces is that single force which will just prevent the motion which the given forces tend to produce.* It is equal and opposite to the resultant and has the same point of application.

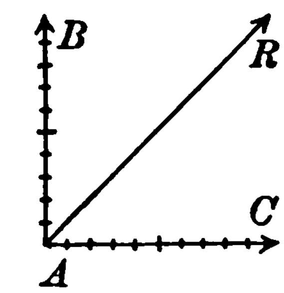


FIG. 59. Direction of resultant of two equal forces at right angles

79. The resultant of forces acting at an angle (concurrent forces). If a body at A is pulled toward the east with a force of 10 lb. (represented in Fig. 59 by the line AC) and toward the north with a force of 10 lb. (represented in the figure by the line AB), the effect upon the motion of the body must, of course, be the same as though some single force acted somewhere between AC and AB. If the body *moves* under the action of the two equal forces, it may be seen from symmetry that it must move along a line midway between AC and AB, that is, along the line AR. This line, therefore, indicates the *direction* as well as the point of application of the resultant of the forces AC and AB.

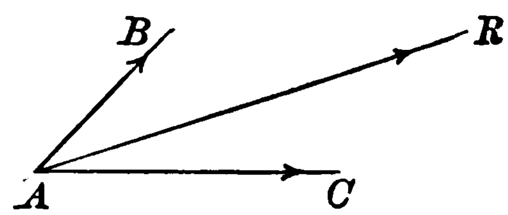


FIG. 60. The resultant lies nearer the larger force

If the two forces are not equal, as in Fig. 60, then the resultant will lie nearer the larger force. The following experiment will show the relation between the two forces and their resultant.

Let the rings of two spring balances be hung over nails B and C in the rail at the top of the blackboard (Fig. 61), and let a weight W be tied near the middle of the string joining the hooks of the two balances. The weight W is not supported by the pull of the balance E or by that of F; it is supported by their resultant, which evidently must act vertically upward, since the only *single* force capable of supporting the weight W is one that is equal and opposite to W. Let the lines OA and OD be drawn upon the blackboard behind the string, and upon these lines lay off the distances Oa and Ob, which contain as many units of length as there are units of force indicated by the balances E and F respectively. Similarly, on a vertical line from O lay off the exact distance OR required to represent the force that supports the weight. This, as noted above, represents the resultant. Now let a parallelogram be constructed upon Oa and Ob as sides. The line OR already drawn will be the diagonal.

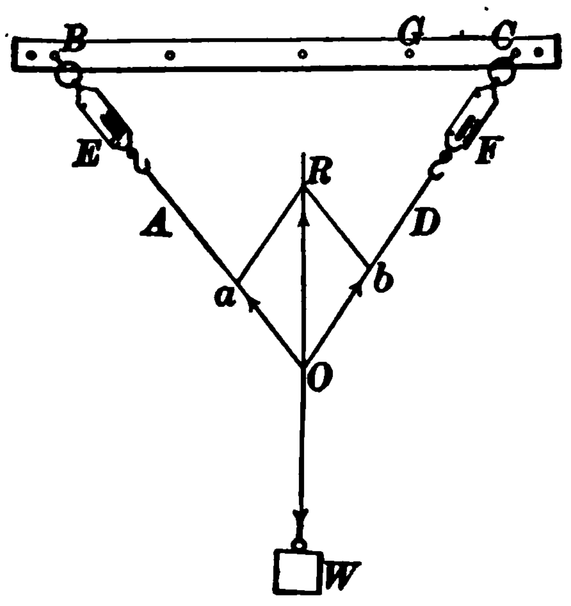


FIG. 61. Experimental proof of parallelogram law

Hence, *to find graphically the resultant of two concurrent forces, (1) represent the concurrent forces, (2) construct upon them as sides a parallelogram, and (3) draw a diagonal from the point of application. This diagonal represents the point of application, direction, and magnitude of the resultant.*

80. Component of a force. Whenever a force acts upon a body in some direction other than that in which the body is free to move, it is clear that the full effect of the force cannot be spent in producing motion. For example, suppose that a force is applied in the direction OR (Fig. 62) to a car on an elevated track. Evidently OR produces two distinct effects upon the car: on the one hand, it moves the car along the track; and, on the other, it presses it down against the rails. These two effects

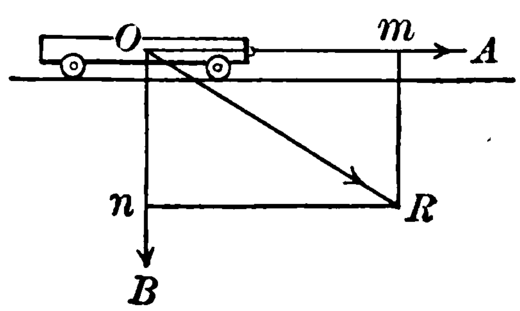


FIG. 62. Component of a force

might be produced just as well by two separate forces acting in the directions OA and OB respectively. The value of the single force which, acting in the direction OA, will produce the same motion of the car on the track as is produced by OR, is called the *component* of OR in the direction OA. Similarly, the value of the single force which, acting in the direction OB, will produce the same pressure against the rails as is produced by the force OR, is called the component of OR in the direction OB. In a word, *the component of a force in a given direction is the effective value of the force in that direction.*

81. Magnitude of the component of a force in a given direction. Since, from the definition of component just given, the two forces, one to be applied in the direction OA and the other in the direction OB, are together to be exactly equivalent to OR in their effect on the car, their magnitudes must be represented by the sides of a parallelogram of which OR is the diagonal. For in § 79 it was shown that if any one force is to have the same effect upon a body as two forces acting simultaneously, it must be represented by the diagonal of a parallelogram the sides of which represent the two forces. Hence, conversely, if two forces are to be equivalent in their joint effect to a single force, they must be sides of the parallelogram of which the single force is the diagonal. Hence the following rule: *To find the component of a force in any given direction, represent the force by a line; then, using the line as a diagonal, construct upon it a rectangle the sides of which are respectively parallel and perpendicular to the direction of the required component. The length of the side which is parallel to the given direction represents the*

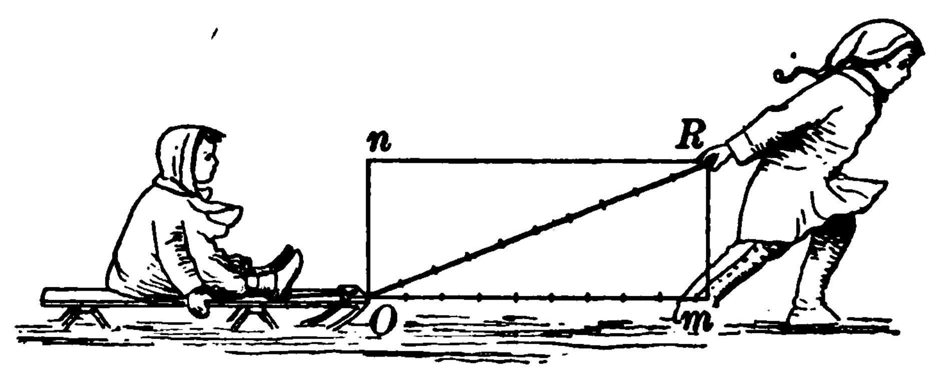


FIG. 63. Horizontal component of pull on a sled

magnitude of the component which is sought. Thus, in Fig. 62 the line *Om* completely represents the component of *OR* in the direction *OA*, and the line *On* represents the component of *OR* in the direction *OB*.

Again, when a boy pulls on a sled with a force of 10 lb. in the direction *OR* (Fig. 63), the force with which the sled is urged forward is represented by the length of *Om*, which is seen to be but 9.3 lb. instead of 10 lb. The component which tends to lift the sled is represented by *On*.

To apply the test of experiment to the conclusions of the preceding paragraph, let a wagon be placed upon an inclined plane (Fig. 64), the height of which, *bc*, is equal to one half its length *ab*. In this case the force acting on the wagon is the weight of the wagon, and its direction is downward. Let this force be represented by the line *OR*. Then, by the construction of the preceding paragraph, the line *Om* will represent the value of the force which is pulling the carriage down the plane, and the line *On* the value of the force which is producing pressure against the plane. Now, since the triangle *ROm* is similar to the triangle *abc* (for $\angle mOR = \angle abc$, $\angle RmO = \angle acb$, and $\angle ORm = \angle bac$), we have

$$\frac{Om}{OR} = \frac{bc}{ab};$$

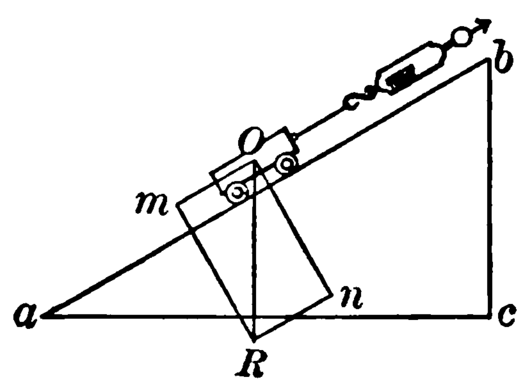


FIG. 64. Component of weight parallel to an inclined plane

that is, in this case, since *bc* is equal to one half of *ab*, *Om* is one half of *OR*. Therefore the force which is necessary to prevent the wagon from sliding down the plane should be equal to one half its weight. To test this conclusion let the wagon be weighed on the spring balance and then placed on the plane in the manner shown in the figure. The pull indicated by the balance will, indeed, be found to be one half the weight of the wagon.

The equation $Om/OR = bc/ab$ gives us the following rule for finding the force necessary to prevent a body from moving down an inclined plane, namely, *the force which must be applied to a body to hold it in place upon an inclined plane bears the same ratio to the weight of the body as the height of the plane bears to its length.*

82. Component of gravity effective in producing the motion of the pendulum. When a pendulum is drawn aside from its position of rest (Fig. 65), the force acting on the bob is its weight, and the direction of this force is vertical. Let it be represented by the line *OR*. The component of this force in the direction in which the bob is free to move is *On*, and the component at right angles to this direction is *Om*. The second component *Om* simply produces stretch in the string and pressure upon the point of suspension. The first component *On* is alone responsible for the motion of the bob. A consideration of the figure shows that this component becomes larger and larger the greater the displacement of the bob. When the bob is directly beneath the point of support, the component producing motion is zero. Hence a pendulum can be permanently at rest only when its bob is directly beneath the point of suspension.*

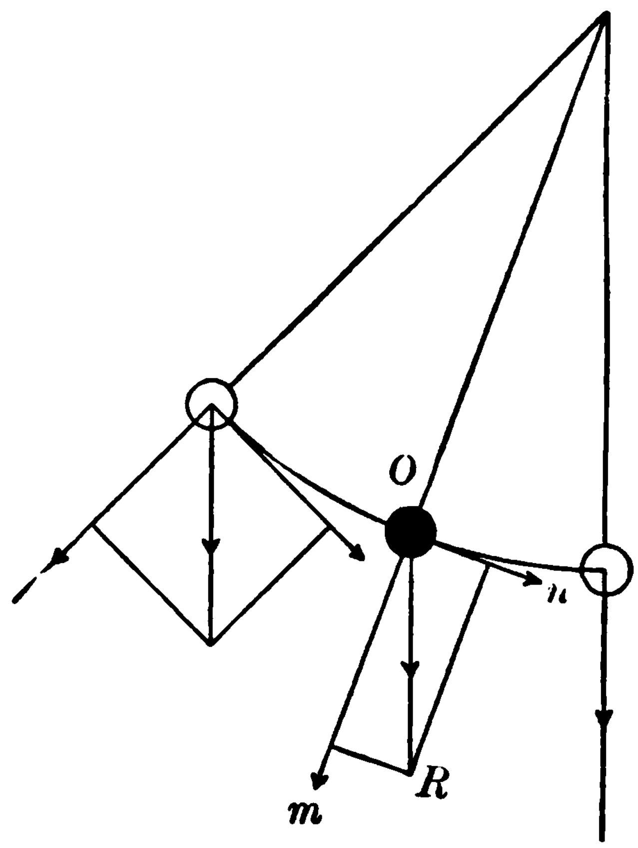


FIG. 65. Force acting on displaced pendulum

QUESTIONS AND PROBLEMS

1. The engines of a steamer can drive it 12 mi. per hour. How fast can it go up a stream in which the current is 3 mi. per hour? How fast can it come down the same stream?

2. The wind drives a steamer east with a force which would carry it 12 mi. per hour, and its propeller is driving it south with a force which would carry it 15 mi. per hour. What distance will it actually travel in an hour? Draw a diagram to represent the exact path.

* It is recommended that the study of the laws of the pendulum be introduced into the laboratory work at about this point (see Experiment 12, authors' Manual).

3. A barge is anchored in a river during a storm. If the wind acts eastward on it with a force of 3000 lb. and the tide northward with a force of 4000 lb., what is the direction and magnitude of the equilibrant; that is, the pull of the anchor cable upon the barge?

4. A picture weighing 20 lb. hangs upon a cord whose parts make an angle of 120° with each other. Find the tension (pull) upon each part of the cord.

5. If the barrel of Fig. 66 weighs 200 lb., with what force must a man push parallel to the skid to keep the barrel in place if the skid is 9 ft. long and the platform 3 ft. high?

Fig. 66. Force necessary to prevent a barrel from rolling down an inclined plane

6. A cake of ice weighing 200 lb. is held at rest upon an inclined plane 12 ft. long and 3 ft. high. By the resolution-and-proportion method find the component of its weight that tends to make the ice slide down the incline. With what force must one push to keep the ice at rest? How great is the component that tends to break the incline?

7. A tight-rope 20 ft. long is depressed 1 ft. at the center when a man weighing 120 lb. stands upon it. Determine graphically the tension in the rope.

8. The anchor rope of a kite balloon makes an angle of 60° with the surface of the earth. If the lifting power of the balloon is 1000 lb., find the pull of the balloon on the rope and the horizontal force of the wind against the balloon.

9. A canal boat and the engine towing it move in parallel paths which are 50 ft. apart. The tow rope is 130 ft. long, and the force (effort) applied to the end of the rope is 1300 lb. Find what component of the 1300 lb. acts parallel to the path of the boat.

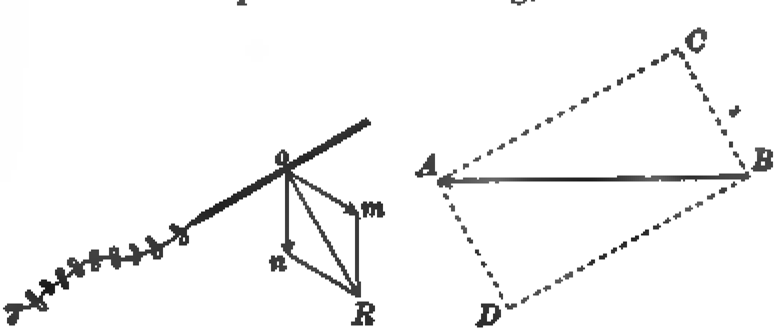


Fig. 67. Forces acting on a kite

10. In Fig. 67 the line *on* represents the pull of gravity on a kite, and the line *om* represents the pull of the boy on the string. What is the name given to the force represented by the line *oR*?

11. If the force of the wind against the kite is represented by the line AB, and it is considered to be applied at o, what must be the relation between the force oR and the component of AB parallel to oR when the kite is in equilibrium under the action of the existing forces?

12. If the wind increases, why does the kite rise higher?

13. Show from Fig. 68 what force supports an aëroplane in flight. (Remember that oR, the component of the wind pressure AB perpendicular to the plane, is the only acting force out of which a support for the aëroplane can be derived.) (See frontispiece and opposite pp. 153, 316, and 317.)

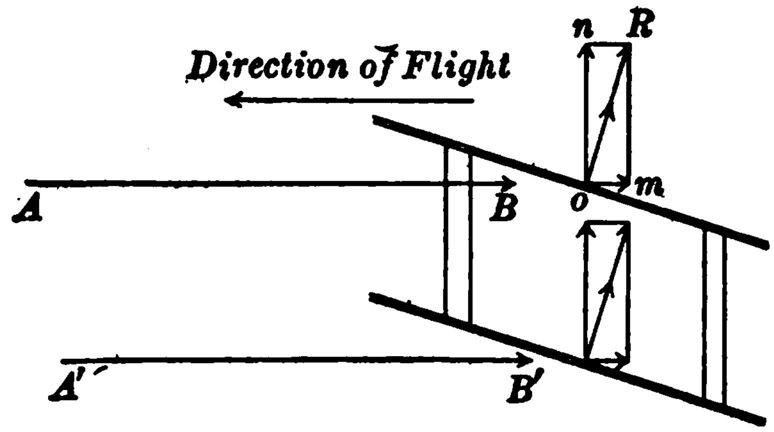


FIG. 68. Forces acting on an aëroplane in flight

GRAVITATION

83. Newton's law of universal gravitation. In order to account for the fact that the earth pulls bodies toward itself, and at the same time to account for the fact that the moon and planets are held in their respective orbits about the earth and the sun, Sir Isaac Newton (1642–1727) (see opposite p. 84) first announced the law which is now known as the law of universal gravitation. This law asserts first that *every body in the universe attracts every other body with a force which varies inversely as the square of the distance between the two bodies.* This means that if the distance between the two bodies considered is doubled, the force will become only one fourth as great; if the distance is made three, four, or five times as great, the force will be reduced to one ninth, one sixteenth, or one twenty-fifth of its original value; etc.

The law further asserts that if the distance between two bodies remains the same, *the force with which one body attracts the other is proportional to the product of the masses of the two bodies.* Thus we know that the earth attracts 3 cubic centimeters of water with three times as much force as it attracts

1, that is, with a force of 3 grams. We know also, from the facts of astronomy, that if the mass of the earth were doubled, its diameter remaining the same, it would attract 3 cubic centimeters of water with twice as much force as it does at present, that is, with a force of 6 grams (multiplying the mass of one of the attracting bodies by 3 and that of the other by 2 multiplies the forces of attraction by 3×2, or 6). In brief, then, Newton's law of universal gravitation is as follows: *Any two bodies in the universe attract each other with a force which is directly proportional to the product of the masses and inversely proportional to the square of the distance between them.*

Two masses of 1 gram each at a distance apart of 1 cm. attract each other with a force of about $\frac{1}{15,000,000,000}$ gram. The masses of the sun and the earth are so great that even though 93,000,000 miles apart, they attract each other with a force of about 4,000,000,000,000,000,000 tons. A body weighing 100 pounds on the earth would weigh about 2700 pounds on the sun. A freely falling body on the earth drops 16 feet the first second, while on the sun it would fall 27 times that far in the first second, or 432 feet. On the moon we should weigh $\frac{1}{6}$ of what we do on the earth; we could jump 6 times as high and should fall $\frac{1}{6}$ as fast.

84. Variation of the force of gravity with distance above the earth's surface. If a body is spherical in shape and of uniform density, it attracts external bodies with the same force as though its mass were concentrated at its center. Since, therefore, the distance from the surface to the center of the earth is about 4000 miles, we learn from Newton's law that the earth's pull upon a body 4000 miles above its surface is but one fourth as much as it would be at the surface.

It will be seen, then, that if a body be raised but a few feet or even a few miles above the earth's surface, the decrease in its weight must be a very small quantity, for the reason that a few feet or a few miles is a small distance compared with

4000 miles. As a matter of fact, at the top of a mountain 4 miles high 1000 grams of mass is attracted by the earth with 998 grams instead of 1000 grams of force.

85. Center of gravity. From the law of universal gravitation it follows that every particle of a body upon the earth's surface is pulled toward the earth. It is evident that the sum of all these little pulls on the particles of which the body is composed must be equal to the total pull of the earth upon the body. Now it is always possible to find one single point in a body at which a single force, equal in magnitude to the weight of the body and directed upward, can be applied so that the body will remain at rest in whatever position it is placed. This point is called the *center of gravity* of the body. Since this force counteracts entirely the earth's pull upon the body, it must be equal and opposite to the resultant of all the small forces which gravity is exerting upon the different particles of the body. Hence the center of gravity may be defined as the point of application of the resultant of all the little downward forces of gravity acting upon the parts of the body; that is, *the center of gravity of a body is the point at which the entire weight of the body may be considered as concentrated.* The earth's attraction for a body is therefore always considered not as a multitude of little forces but as one single force F (Fig. 69) equal to the pull of gravity upon the body and applied at its center of gravity G. It is evident, then, that *under the influence of the earth's pull, every body tends to assume the position in which its center of gravity is as low as possible.*

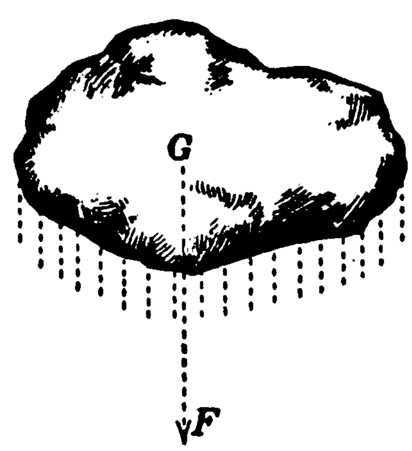


FIG. 69. Center of gravity of an irregular body

86. Method of finding center of gravity experimentally. From the above definition it will be seen that the most direct way of finding the center of gravity of any flat body, like that shown in Fig. 70, is to find the point upon which it will balance.

Let an irregular sheet of zinc be thus balanced on the point of a pencil or the head of a pin. Let a small hole be punched through the zinc at the point of balance, and let a needle be thrust through this hole. When the needle is held horizontally, the zinc will be found to remain at rest, no matter in what position it is turned.

To illustrate another method of finding the center of gravity of the zinc, let it be supported from a pin stuck through a hole near its edge, that is, *b* (Fig. 70). Let a plumb line be hung from the pin, and let a line *bn* be drawn through *b* on the surface of the zinc parallel to and directly behind the plumb line. Let the zinc be hung from another point *a*, and let another line *am* be drawn in a similar way.

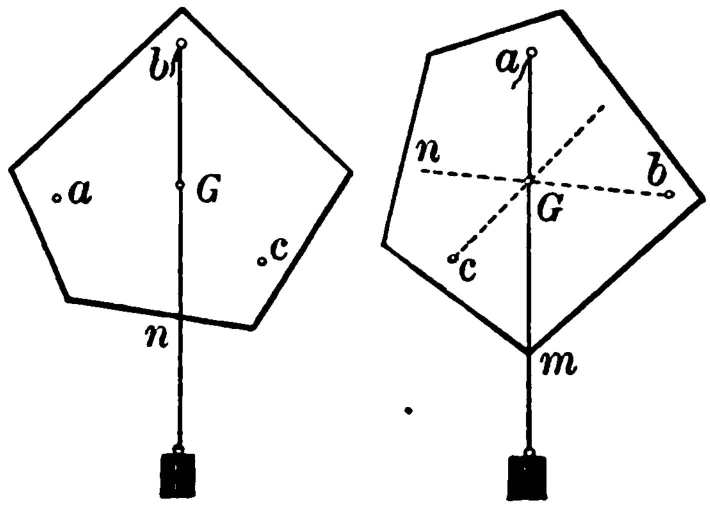


FIG. 70. Locating center of gravity

Since the attraction of the earth for a body may be considered as a single force applied at the center of gravity, a suspended body (for example, the sheet of zinc) can remain at rest only when the center of gravity is directly beneath the point of support (see § 85). It must therefore lie somewhere on the line *am*. For the same reason it must lie on the line *bn*. But the only point which lies on both of these lines is their point of intersection *G*. *The point of intersection, then, of any two vertical lines dropped through two different points of suspension locates the center of gravity of a body.*

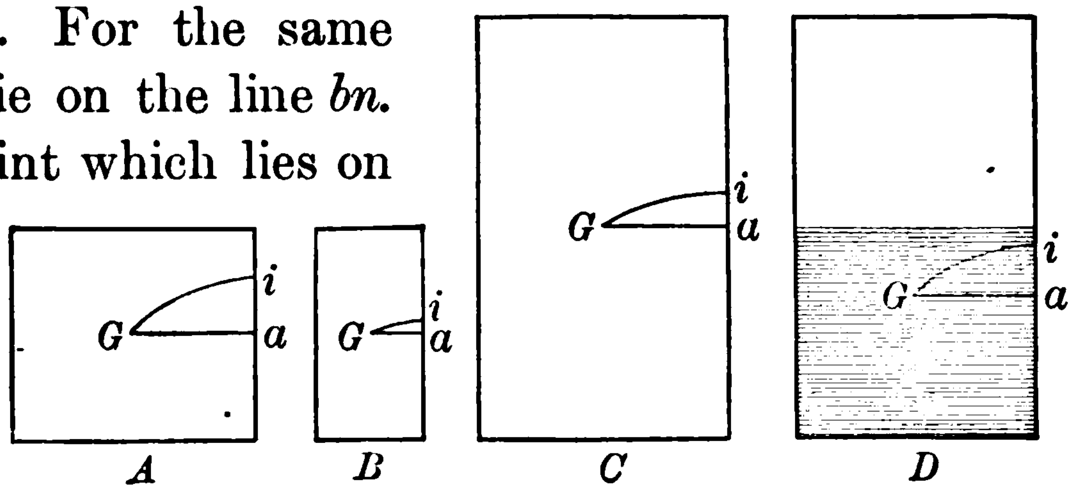


FIG. 71. Illustration of varying degrees of stability

87. Stable equilibrium. A body is said to be in *stable equilibrium* if it tends to return to its original position when very slightly tipped, or rotated, out of that position. A pendulum,

a chair, a cube resting on its side, a cone resting on its base, a boat floating quietly in still water, are all illustrations.

In general, a body is in stable equilibrium whenever tipping it slightly tends to raise its center of gravity. Thus, in Fig. 71 all of the bodies *A*, *B*, *C*, *D*, are in stable equilibrium, for in order to overturn any one of them its center of gravity

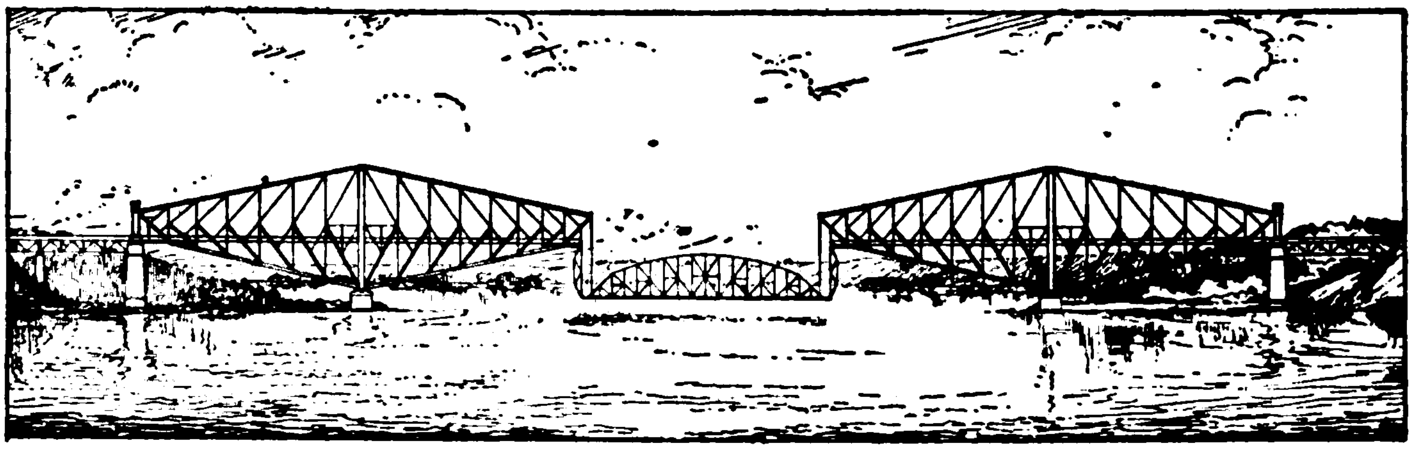


FIG. 72. Quebec bridge

G must be raised through the height *ai*. If the weights are all alike, that one will be most stable for which *ai* is greatest.

In building cantilever bridges such as the large one over the St. Lawrence River at Quebec (Fig. 72) the engineers build out the cantilever arms equally in opposite directions, so as to keep their centers of gravity constantly over the piers until the parts either meet at the center or are close enough to receive the central span, which is hoisted to place.

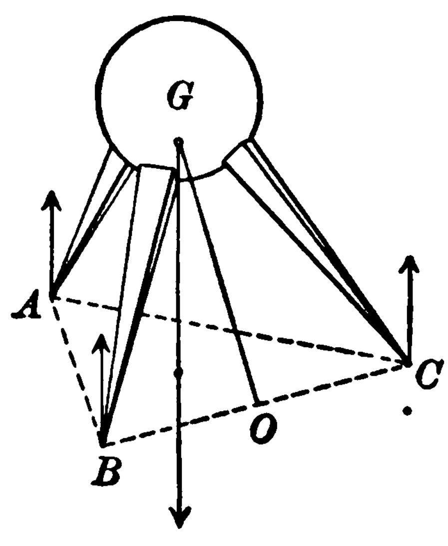


FIG. 73. Body in stable equilibrium

The condition of stable equilibrium for bodies which rest upon a horizontal plane is that a vertical line through the center of gravity shall fall within the base, the base being defined as the polygon formed by connecting the points at which the body touches the plane, as *ABC* (Fig. 73); for it is clear that in such a case a slight displacement must raise the center of gravity along the arc of which *OG* is the radius. If the vertical line drawn through the center of gravity fall outside the base, as in Fig. 74, the body must always fall.

The condition of stable equilibrium for bodies supported from a single point, as in the case of a pendulum, is that the point of support be above the center of gravity. For example, the beam of a balance cannot be in stable equilibrium, so that it will return to the horizontal position when slightly displaced, unless its center of gravity g (Fig. 3, p. 7) is below the knife-edge C. (The pans are not to be considered, since they are not rigidly connected to the beam.)

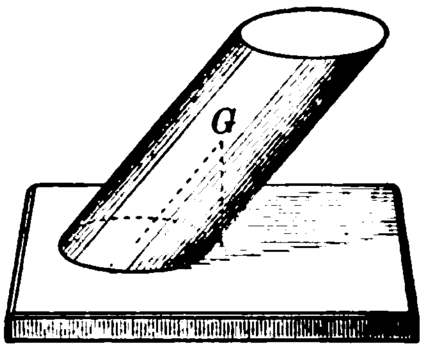


FIG. 74. Body not in equilibrium

88. Neutral and unstable equilibrium. A body is said to be in *neutral equilibrium* when, after a slight displacement, it tends neither to return to its original position nor to move farther from it. Examples of neutral equilibrium are a spherical ball lying on a smooth plane, a cone lying on its side, a wheel free to rotate about a fixed axis through its center, or any body supported at its center of gravity. In general, a body is in neutral equilibrium when a slight displacement neither raises nor lowers its center of gravity.

A body is in *unstable equilibrium* when, after a slight tipping, it tends to move farther from its original position. A cone balanced on its point or an egg on its end are examples. In all such cases a slight tipping lowers the center of gravity, and the motion then continues until the center of gravity is as low as circumstances will permit. The condition for unstable equilibrium in the case of a body supported by a point is that the center of gravity shall be above the point of support.

QUESTIONS AND PROBLEMS

1. Explain why the toy shown in Fig. 75 will not lie upon its side, but rises to the vertical position. Does the center of gravity rise?

2. Where is the center of gravity of a hoop? of a cubical box? Is the latter more stable when empty or when full? Why?

3. Where must the center of gravity of the beam of a balance be with reference to the supporting knife-edge C? (Fig. 3, p. 7.) Why? Could you make a weighing if C and g coincided? Why?

4. What is the object of ballast in a ship?

5. What is the most stable position of a brick? the least stable? Why?

6. In what state of equilibrium is a pendulum at rest? Why?

7. What purpose is served by the tail of a kite?

8. Do you get more sugar to the pound in Calcutta than in Aberdeen when using a beam balance? when using a spring balance? Explain.

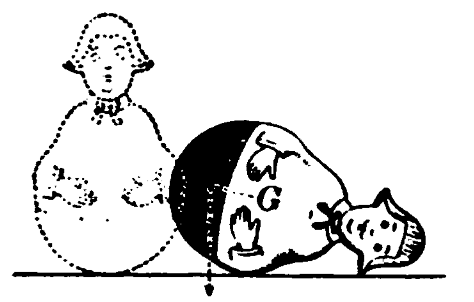


FIG. 75

9. What change would there be in your weight if your mass were to become four times as great and that of the earth three times, the radius of the earth remaining the same?

10. The pull of the earth on a body at its surface is 100 kg. Find the pull on the same body 4000 mi. above the surface; 1000 mi. above the surface; 3 mi. above the surface. (Take the earth's radius as 4000 mi.)

FALLING BODIES

89. Galileo's early experiments. Many of the familiar and important experiences of our lives have to do with falling bodies. Yet when we ask ourselves the simplest question which involves quantitative knowledge about gravity, such as, for example, Would a stone and a piece of lead dropped from the same point reach the ground at the same time or at different times? most of us are uncertain as to the answer. In fact, it was the asking and the answering of this very question by Galileo, about 1590, which may be considered as the starting point of modern science.

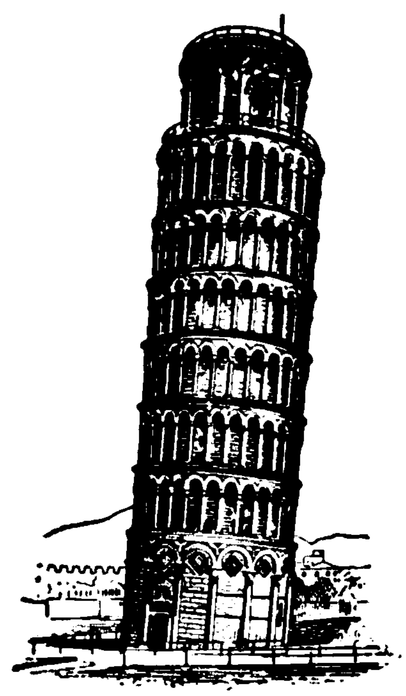


FIG. 76. Leaning tower of Pisa, from which were performed some of Galileo's famous experiments on falling bodies

Ordinary observation teaches that light bodies like feathers fall slowly and heavy bodies like stones fall rapidly, and up to Galileo's time it was taught in the schools that bodies fall with "velocities proportional to their weights." Not content with book knowledge, however,

GALILEO (1564–1642)

Great Italian physicist, astronomer, and mathematician; "founder of experimental science"; was son of an impoverished nobleman of Pisa; studied medicine in early youth, but forsook it for mathematics and science; was professor of mathematics at Pisa and at Padua; discovered the laws of falling bodies and the laws of the pendulum; was the creator of the science of dynamics; constructed the first thermometer; first used the telescope for astronomical observations; discovered Jupiter's satellites and the spots on the sun. Modern physics begins with Galileo

"FIRE"

Pounding the German lines opposite Baleycourt Woods, near Nixeville, Department of the Meuse, with French 340-mm. guns manned by Yankee coast artillerymen of the 35th Coast Artillery. This gun hit two German army corps headquarters 30 kilometers distant, September 26, 1918

Galileo tried it himself. In the presence of the professors and students of the University of Pisa he dropped balls of different sizes and materials from the top of the tower of Pisa (Fig. 76), 180 feet high, and found that they fell in practically the same time. He showed that even very light bodies like paper fell with velocities which approached more and more nearly those of heavy bodies the more compactly they were wadded together. From these experiments he inferred that *all bodies, even the lightest, would fall at the same rate if it were not for the resistance of the air.*

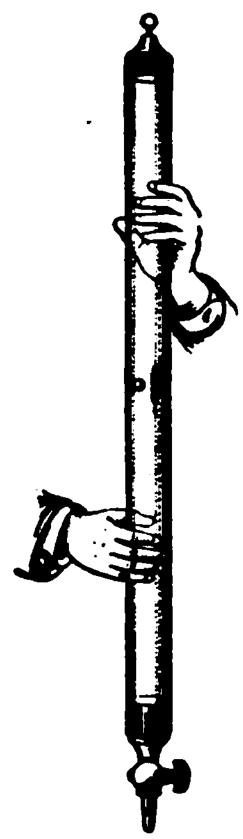


FIG. 77. Feather and coin fall together in a vacuum

That the air resistance is indeed the chief factor in the slowness of fall of feathers and other light objects can be shown by pumping the air out of a tube containing a feather (or some small pieces of tissue paper) and a coin (Fig. 77). The more complete the exhaustion the more nearly do the feather and the coin fall side by side when the tube is inverted. The air pump, however, was not invented until sixty years after Galileo's time.

90. Exact proof of Galileo's conclusion. We can demonstrate the correctness of Galileo's conclusion in still another way, one which he himself used.

Let balls of iron and wood, for example, be started together down the inclined plane of Fig. 78. They will be found to keep together all the

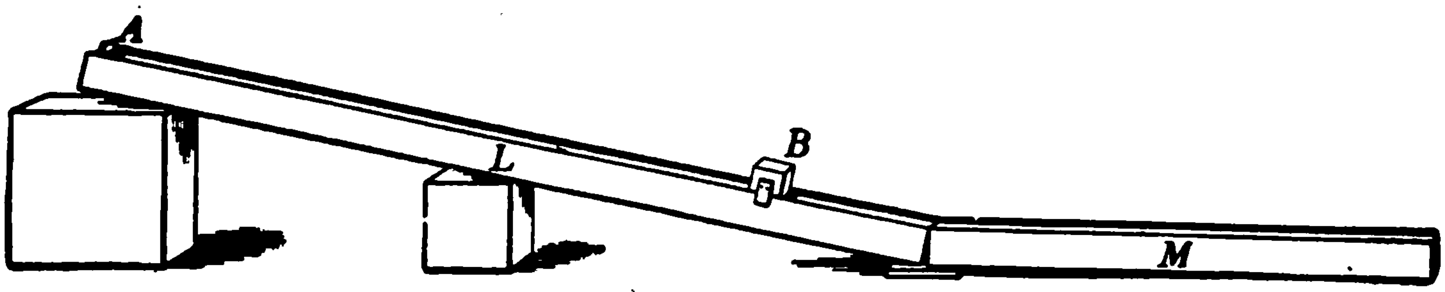


FIG. 78. Spaces traversed and velocities acquired by falling bodies in one, two, three, etc. seconds

way down. (If they roll in a groove, they should have the same diameter; otherwise, size is immaterial.) The experiment differs from that

of the freely falling bodies only in that the resistance of the air is here more nearly negligible because the balls are moving more slowly. In order to make them move still more slowly and at the same time to eliminate completely all possible effects due to the friction of the plane, let us follow Galileo and suspend the different balls as the bobs of pendulums of exactly the same length, two meters long at least, and start them swinging through equal arcs. Since now the bobs, as they pass through any given position, are merely moving very slowly down identical inclined planes (Fig. 65), it is clear that this is only a refinement of the last experiment. We shall find that the times of fall, that is, *the periods*, of the pendulums are exactly the same.

From the above experiment we conclude with Galileo and with Newton, who performed it with the utmost care a hundred years later, that *in a vacuum the velocity acquired per second by a freely falling body is exactly the same for all bodies.*

91. Relation between distance and time of fall. Having found that, barring air resistance, all bodies fall in exactly the same way, we shall next try to find what relation exists between distance and time of fall; and since a freely falling body falls so rapidly as to make direct measurements upon it difficult, we shall adopt Galileo's plan of studying the laws of falling bodies through observing the motions of a ball rolling down an inclined plane.

Let a grooved board 17 or 18 ft. long be supported as in Fig. 78, one end being about a foot above the other. Let the side of the board be divided into feet, and let the block *B* be set just 16 ft. from the starting point of the ball *A*. Let a metronome or a clock beating seconds be started, and let the marble be released at the instant of one click of the metronome. If the marble does not hit the block so that the click produced by the impact of the ball coincides exactly with the fifth click of the metronome, alter the inclination until this is the case. (This adjustment may well be made by the teacher before class.) Now start the marble again at some click of the metronome, and note that it crosses the 1-ft. mark exactly at the end of the first second, the 4-ft. mark at the end of the second second, the 9-ft. mark at the end of the third second, and hits *B* at the 16-ft. mark at the end of the fourth second. This can be tested more accurately by placing *B* successively at the

9-ft., the 4-ft., and the 1-ft. mark and noting that the click produced by the impact coincides exactly with the proper click of the metronome.

We conclude, then, with Galileo, that *the distance traversed by a falling body in any number of seconds is the distance traversed the first second times the square of the number of seconds;* that is, if D represents the distance traversed the first second, S the total space, and t the number of seconds, $S = Dt^2$.

92. Relation between velocity and time of fall. In the last paragraph we investigated the distances traversed in one, two, three, etc. seconds. Let us now investigate the *velocities* acquired on the same inclined plane in one, two, three, etc. seconds.

Let a second grooved board M be placed at the bottom of the incline, in the manner shown in Fig. 78. To eliminate friction it should be given a slight slant, just sufficient to cause the ball to roll along it with uniform velocity. Let the ball be started at a distance D up the incline, D being the distance which in the last experiment it was found to roll during the first second. It will then just reach the bottom of the incline at the instant of the second click. Here it will be freed from the influence of gravity, and will therefore move along the lower board with the velocity which it had at the end of the first second. It will be found that when the block is placed at a distance exactly equal to $2\ D$ from the bottom of the incline, the ball will hit it at the exact instant of the third click of the metronome, that is, exactly two seconds after starting; hence the velocity acquired in one second is $2\ D$. If the ball is started at a distance $4\ D$ up the incline, it will take it two seconds to reach the bottom, and it will roll a distance $4\ D$ in the next second; that is, in two seconds it acquires a velocity $4\ D$. In three seconds it will be found to acquire a velocity $6\ D$, etc.

The experiment shows, first, that the gain in velocity each second is the same; second, that the amount of this gain is numerically equal to twice the distance traversed the first second. *Motion*, like the above, *in which velocity is gained at a constant rate is called uniformly accelerated motion.*

In uniformly accelerated motion the gain each second in the velocity is called the acceleration. It is numerically equal to twice the distance traversed the first second.

93. Formal statement of the laws of falling bodies. Putting together the results of the last two paragraphs, we obtain the following table, in which D represents the distance traversed the first second in any uniformly accelerated motion.

Number of Seconds (t)	Velocity at the End of Each Second (v)	Gain in Velocity Each Second (a)	Total Distance Traversed (S)
1	$2D$	$2D$	$1D$
2	$4D$	$2D$	$4D$
3	$6D$	$2D$	$9D$
4	$8D$	$2D$	$16D$
. . .	. . .	. . .	. . .
t	$2tD$	$2D$	t^2D

Since D was shown, in § 92, to be equal to one half of the acceleration a, we have at once, by substituting $\frac{1}{2}a$ for D in the last line of the table,

$$v = at, \tag{1}$$

$$S = \tfrac{1}{2}at^2. \tag{2}$$

These formulas are simply the algebraic statement of the facts brought out by our experiments, but the reasons for these facts may be seen as follows:

Since in uniformly accelerated motion the acceleration a is the velocity in centimeters per second gained each second, it follows at once that when a body starts from rest, the velocity which it has at the end of t seconds is given by $v = at$. This is formula (1).

To obtain formula (2) we have only to reflect that distance traversed is always equal to the average velocity multiplied by the time. When the initial velocity is zero, as in this case, and the final velocity is at, average velocity $= (0 + at) \div 2 = \frac{1}{2}at$. Hence

$$S = \tfrac{1}{2}at^2.$$

This is formula (2).

These are the fundamental formulas of uniformly accelerated motion, but it is sometimes convenient to obtain the final velocity v directly from the total distance of fall S, or vice versa. This may of course be done by simply substituting in (2) the value of t obtained from (1), namely, $\frac{v}{a}$. This gives

$$v = \sqrt{2aS}. \tag{3}$$

94. Acceleration of a freely falling body. If in the above experiment the slope of the plane be made steeper, the results will obviously be precisely the same, except that the acceleration has a larger value. If the board is tilted until it becomes vertical, the body becomes a freely falling body (Fig. 79). In this case the distance traversed the first second is found to be 490 centimeters, or 16.08 feet. Hence the acceleration, expressed in centimeters, is 980; in feet, 32.16. This acceleration of free fall, called the *acceleration of gravity*, is usually denoted by the letter g. For freely falling bodies, then, the three formulas of the preceding paragraph become

$$v = gt, \qquad (4)$$

$$S = \tfrac{1}{2} gt^2, \qquad (5)$$

$$v = \sqrt{2\, gS}. \qquad (6)$$

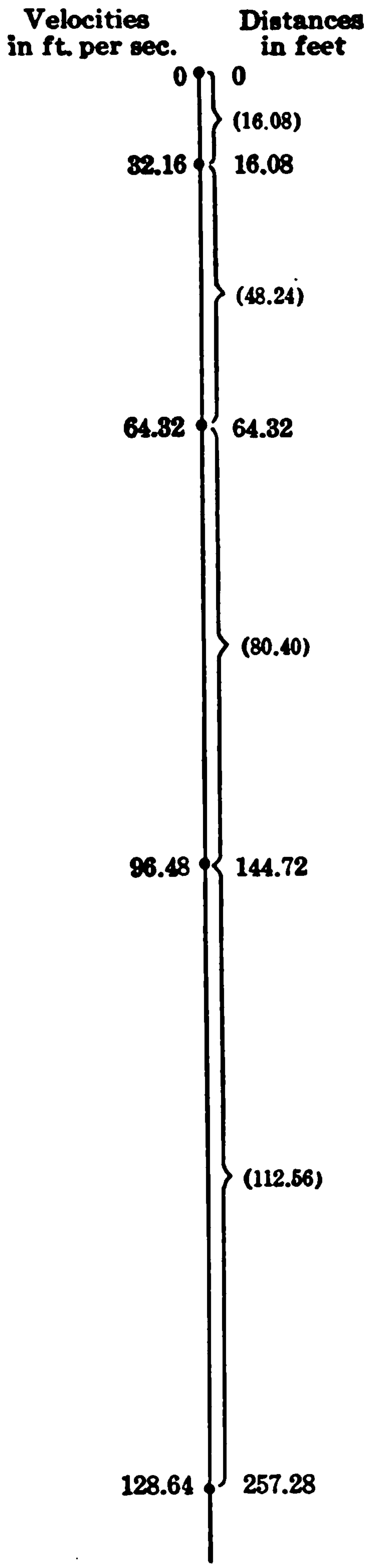


FIG. 79. A freely falling body

To illustrate the use of these formulas, suppose we wish to know with what velocity a body will hit the earth if it falls from a height of 200 meters, or 20,000 centimeters. From (6) we get

$$v = \sqrt{2 \times 980 \times 20{,}000} = 6261 \text{ cm. per second.}$$

95. Height of ascent. If we wish to find the height S to which a body projected vertically upward will rise, we reflect that the time of ascent must be the initial velocity divided by the upward velocity which the body loses per second, that is, $t = \frac{v}{g}$; and the height reached

must be this multiplied by the average velocity $\frac{v+0}{2}$; that is,

$$S = \frac{v^2}{2g}, \quad \text{or} \quad v = \sqrt{2gS}. \tag{7}$$

Since (7) is the same as (6), we learn that in a vacuum the speed with which a body must be projected upward to rise to a given height is the same as the speed which it acquires in falling from the same height.

96. Path of a projectile. Imagine a projectile to be shot along the line *ab* (Fig. 80). If it were not for gravity and the resistance of the air, the projectile would travel with uniform velocity along the line *ab*, arriving at the points 1, 2, 3, etc. at the end of the successive seconds. Because of gravity, however, the projectile would be vertically below these points by the distances 16.08 ft., 64.32 ft., 144.72 ft., etc. Hence it would follow the path indicated by the dotted curve (a parabola). But because of air resistance the height of flight and range are diminished, and the general shape of the trajectory is similar to the continuous curved line.

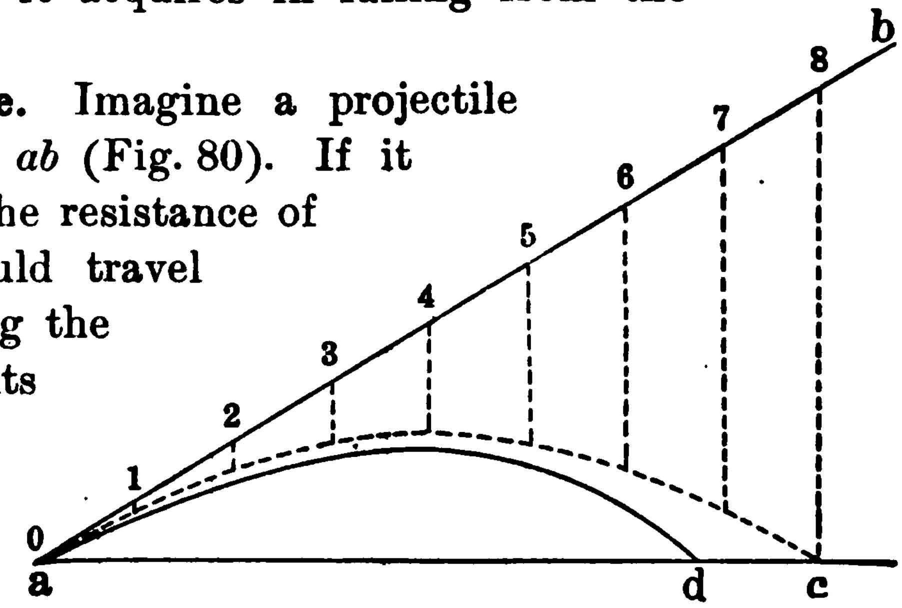


FIG. 80. Path of a projectile

97. The airplane. The principles underlying stability, as well as those having to do with the resolution of forces, are well illustrated by the modern airplane, which grew out of a study of *the laws of air resistance* and *the properties of gliders.*

When a plate of area A moves in still air in a direction perpendicular to its plane, with a velocity V (see Fig. 81, (1)), the air resistance R is found by experiment to be given by the equation

$$R = KAV^2, \tag{8}$$

where R is the force in kilograms, A the area in square meters, V the speed in meters per second, and K a constant which has the value .08. Thus, when an automobile is going 40 miles

per hour (18 meters per second), the force of the air against .5 square meter of wind-shield is $.08 \times .5 \times (18)^2 = 13$ kg.

When the plate moves so that the direction of its motion makes a small angle i (between 0° and 10°) (Fig. 81, (2)) with its plane, the air resistance R is perpendicular to the plate and is given by the empirical formula

$$R = kAV^2 i, \qquad (9)$$

where R, A, and V have the same significance as above, i is the angle in degrees, and k is very near to .005.

As i, which is called *the angle of attack* or *of incidence*, decreases, the center of pressure C (Fig. 81, (2)) moves

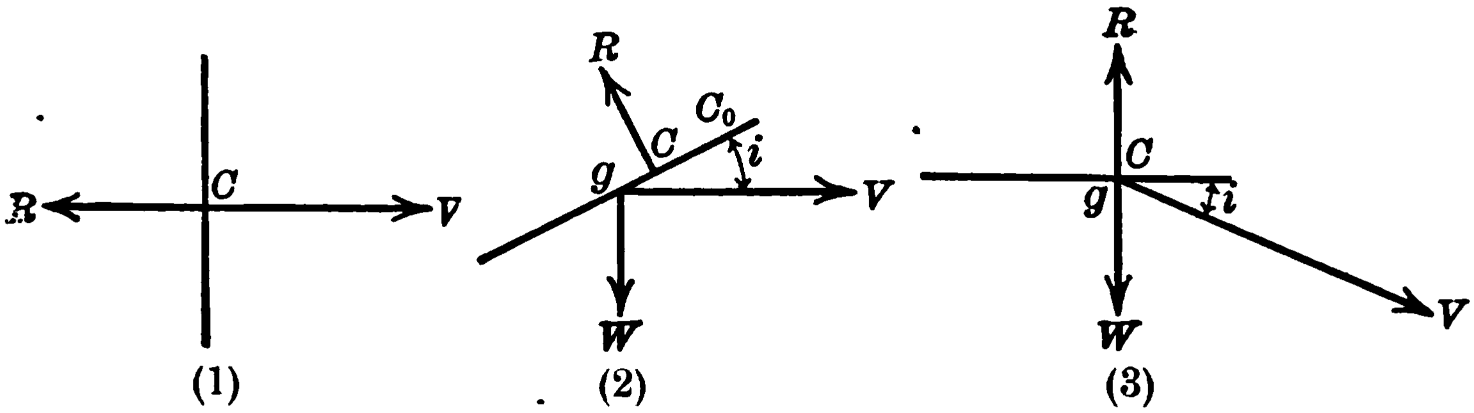


FIG. 81. Forces acting on a glider

toward the front edge and tends toward a certain definite limiting position C_0 as the angle i becomes smaller and smaller.

When a flat object like a sheet of paper is allowed to fall, it is acted upon by two forces, one W, acting at its center of gravity g, which is always vertical and equal to the weight, and the other R, which is due to the air resistance acting at the center of pressure C and perpendicular to the plane. If the plane is to fall without acceleration and without rotation, that is, if it is to *glide*, it is clear that these two forces must act at the same point and be equal and opposite. Hence *any gliding plane must be horizontal* and must move with a speed V at an angle i (see Fig. 81 (3)), given by the equation

$$R = W = .005\ V^2 Ai. \qquad (10)$$

Since the plane must be horizontal, and since there is only one angle of attack which will bring the center of pressure and the center of gravity together, it will be seen that the gliding angle i is the same for all values of the weight W, but that the speed V will be proportional to the square root of the weight (see equation 10).

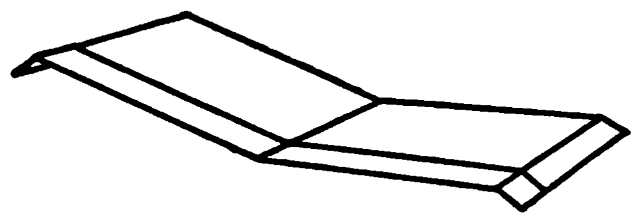


FIG. 82. A stabilized glider

The foregoing theory of gliding may be nicely illustrated with paper gliders thus: Fold a sheet of writing paper lengthwise, exactly along the middle. Refold the upper half twice on itself so as to make it $\frac{1}{4}$ its original width; then fasten it down to the lower half with paste or light gummed paper. The center of gravity will now be $\frac{1}{16}$ of the new width behind the back edge of the folded portion. When started slowly with the folded edge forward, the paper will glide as described. Heavier paper will glide at the same angle but with greater speed. If started thin edge foremost, the forces at once turn the glider over, and it glides with the heavier edge in front. To increase the lateral stability it is sufficient to give the paper the shape shown in Fig. 82. (See opposite p. 317.)

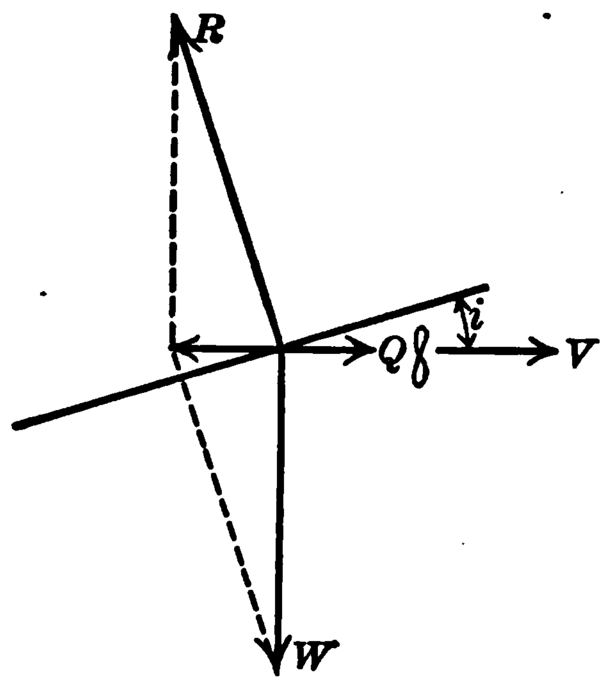


FIG. 83. Forces acting on an airplane in flight

When the motor of an airplane stops, the plane glides safely to earth under the laws of equation 10. If the airplane propeller is pulling forward with a horizontal force Q, and the wings are set back at an angle i, R and W no longer balance each other, but their resultant is equal and opposite to Q; that is, the forces R, W, and Q form a system in equilibrium, as shown in Fig. 83. The plane moves forward horizontally with a speed V. If the angle i or the force Q is increased, the plane rises; if i or Q is diminished, the plane descends.

98. The laws of the pendulum. The first law of the pendulum was found in § 90, namely,

(1) *The periods of pendulum of equal lengths swinging through short arcs are independent of the weight and material of the bobs.*

Let the two pendulums of § 90 be set swinging through arcs of lengths 5 centimeters and 25 centimeters respectively. We shall thus find the second law of the pendulum, namely,

(2) *The period of a pendulum swinging through a short arc is independent of the amplitude of the arc.*

Let pendulums $\frac{1}{4}$ and $\frac{1}{9}$ as long as the above be swung with it. The long pendulum will be found to make only one vibration while the others are making two and three respectively. The third law of the pendulum is therefore

(3) *The periods of pendulums are directly proportional to the square roots of their lengths.*

The accurate determination of g is never made by direct measurement, for the laws of the pendulum just established make this instrument by far the most accurate one obtainable for this determination. It is only necessary to measure the length of a long pendulum and the time t between two successive passages of the bob across the mid-point, and then to substitute in the formula $t = \pi\sqrt{\frac{l}{g}}$ in order to obtain g with a high degree of precision. The deduction of this formula is not suitable for an elementary text, but the formula itself may well be used for checking the value of g, given in § 94.

QUESTIONS AND PROBLEMS

1. If a body starts from rest and travels with a constant acceleration of 10 ft. per second each second, how fast will it be going at the close of the fifth second? What is its average velocity during the 5 sec., and how far did it go in this time?

2. A body starting from rest and moving with uniformly accelerated motion acquired a velocity of 60 ft. per second in 5 sec. Find the acceleration. What distance did it traverse during the first second? the fifth?

3. A body moving with uniformly accelerated motion traversed 6 ft. during the first second. Find the velocity at the end of the fourth second.

4. A ball thrown across the ice started with a velocity of 80 ft. per second. It was retarded by friction at the rate of 2 ft. per second each second. How long did it roll? How far did it roll?

5. A bullet was fired with a velocity of 2400 ft. per second from a rifle having a barrel 2 ft. long. Find (a) the average velocity of the bullet while moving the length of the barrel; (b) the time required to move through the barrel; (c) the acceleration of the bullet while in the barrel.

6. A ball was thrown vertically into the air with a velocity of 160 ft. per second. How long did it remain in the air? (Take $g=32$ ft. per sec^2.)

7. A baseball was thrown upward. It remained in the air 6 sec. With what velocity did it leave the hand? How high did it go?

8. A ball dropped from the top of the Woolworth Building in New York City, 780 ft. above Broadway, would require how many seconds to fall? With what velocity would it strike? (Take $g = 32$ ft. per sec^2.)

9. How high was an airplane from which a bomb fell to earth in 10 sec.?

10. With what speed does a bullet strike the earth if it is dropped from the Eiffel Tower, 335 m. high?

11. If the acceleration of a marble rolling down an inclined plane is 20 cm. per second, what velocity will it have at the bottom, the plane being 7 m. long?

12. If a man can jump 3 ft. high on the earth, how high could he jump on the moon, where g is $\frac{1}{6}$ as much?

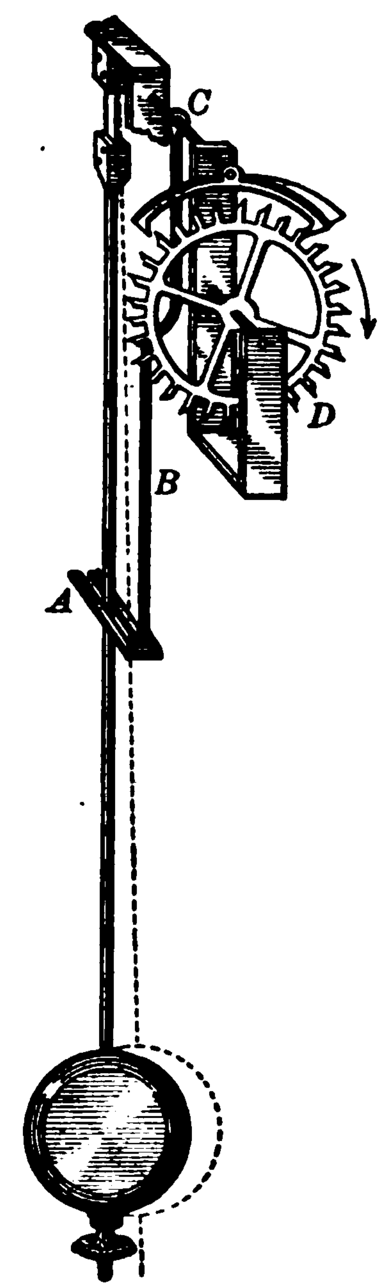


FIG. 84

13. The brakes were set on a train running 60 mi. per hour, and the train stopped in 20 sec. Find the acceleration in feet per second each second and the distance the train ran after the brakes were applied.

14. How far will a body fall from rest during the first half second?

15. With what velocity must a ball be shot upward to rise to the height of the Washington Monument (555 ft.)? How long before it will return?

16. Fig. 84 represents the pendulum and escapement of a clock. The escapement wheel D is urged in the direction of the arrow by the clock weights or spring. The slight pushes communicated by the teeth of the wheel keep the pendulum from dying down. Show how the length of the pendulum controls the rate of the clock.

17. What force supports an airplane in flight? What is "gliding"?

18. A pendulum that makes a single swing per second in New York City is 99.3 cm., or 39.1 in., long. Account for the fact that a seconds pendulum at the equator is 39 in. long, while at the poles it is 39.2 in. long.

19. How long is a pendulum whose period is 3 sec.? 2 sec.? $\frac{1}{2}$ sec.? $\frac{1}{3}$ sec.?

20. A man was let down over a cliff on a rope to a depth of 500 ft. What was his period as a pendulum?

Newton's Laws of Motion

99. First law — inertia. It is a matter of everyday observation that bodies in a moving train tend to move toward the forward end when the train stops and toward the rear end when the train starts; that is, bodies in motion seem to want to keep on moving, and bodies at rest to remain at rest.

Again, a block will go farther when driven with a given blow along a surface of glare ice than when knocked along an asphalt pavement. The reason which everyone will assign for this is that there is more friction between the block and the asphalt than between the block and the ice. But when would the body stop if there were no friction at all?

Astronomical observations furnish the most convincing answer to this question, for we cannot detect any retardation at all in the motions of the planets as they swing around the sun through empty space.

Furthermore, since mud flies off *tangentially* from a rotating carriage wheel, or water from a whirling grindstone, and since, too, we have to lean inward to prevent ourselves from falling outward in going around a curve, it appears that bodies in motion tend to maintain not only the *amount* but also the *direction* of their motion (see gyrocompass opposite p. 223).

In view of observations of this sort Sir Isaac Newton, in 1686, formulated the following statement and called it the first law of motion.

Every body continues in its state of rest or uniform motion in a straight line unless impelled by external force to change that state.

This property, which all matter possesses, of resisting any attempt to start it if at rest, to stop it if in motion, or in any way to change either the direction or amount of its motion, is called inertia.

100. Centrifugal force. It is inertia alone which prevents the planets from falling into the sun, which causes a rotating sling to pull hard on the hand until the stone is released, and which then causes the stone to fly off tangentially. It is inertia which makes rotating liquids move out as far as possible from the axis of rotation (Fig. 85), which makes flywheels sometimes burst, which makes the equatorial diameter of the earth greater than the polar, which makes the heavier milk move out farther than the lighter cream in the dairy separator (see opposite p. 85), etc. *Inertia manifesting itself in this tendency of the parts of rotating systems to move away from the center of rotation is called centrifugal force.*

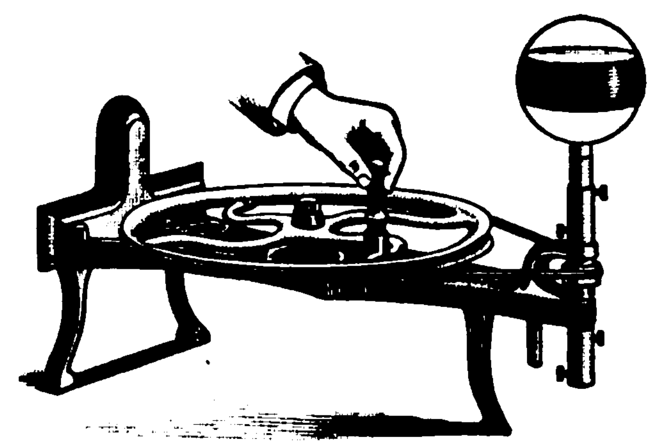


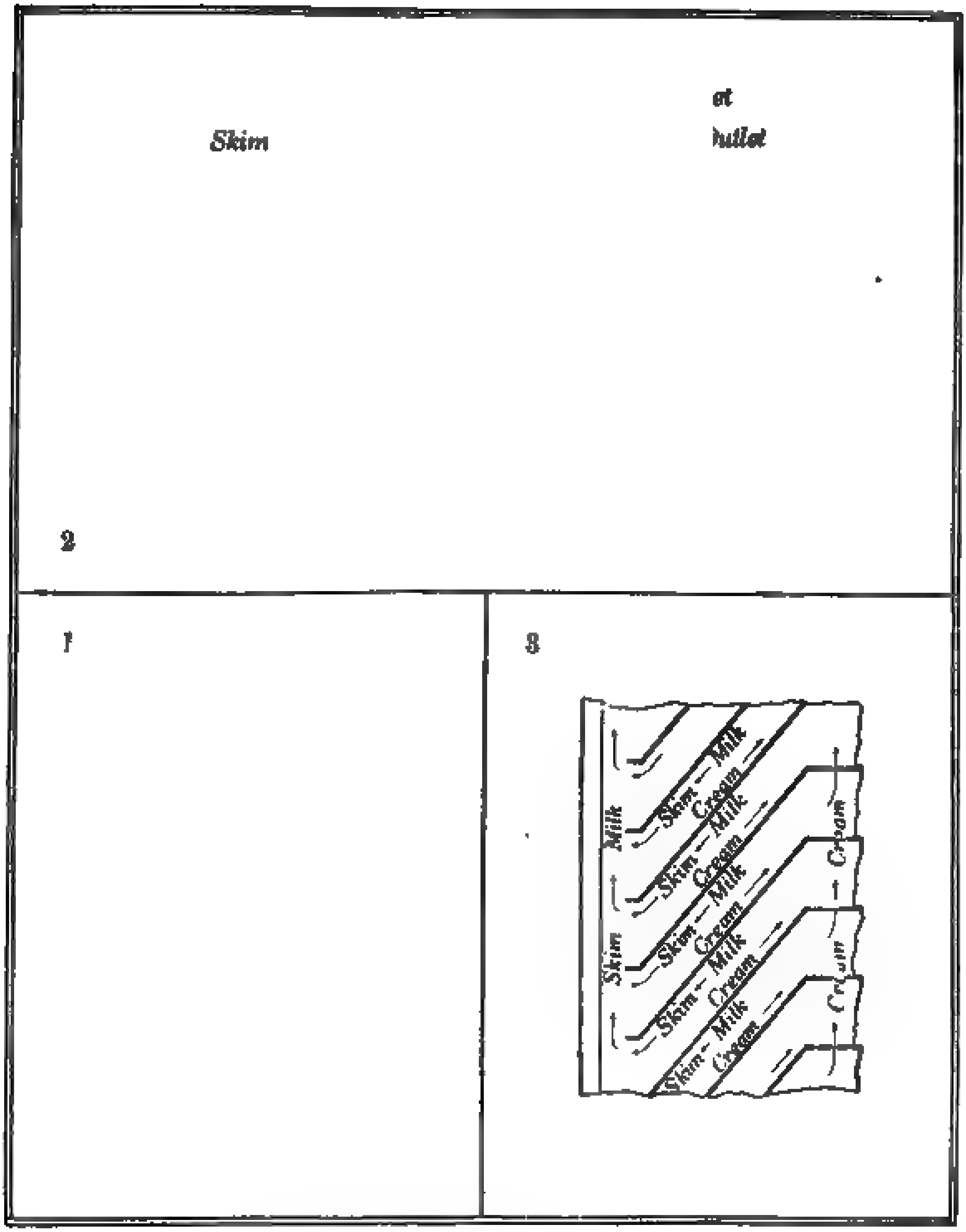
FIG. 85. Illustrating centrifugal force

101. Momentum. The quantity of motion possessed by a moving body is defined as the product of the mass and the velocity of the body. It is commonly called *momentum.* Thus, a 10-gram bullet moving 50,000 centimeters per second has 500,000 units of momentum; a 1000-kg. pile driver moving 1000 centimeters per second has 1,000,000,000 units of momentum; etc. We shall always express momentum in C.G.S. units, that is, as a product of grams by centimeters per second.

102. Second law. Since a 2-gram mass is pulled toward the earth with twice as much force as is a 1-gram mass, and since both, when allowed to fall, acquire the same velocity in

Sɪʀ Isaac Newton (1642–1727)

English mathematician and physicist, "prince of philosophers"; professor of mathematics at Cambridge University; formulated the law of gravitation; discovered the binomial theorem; invented the method of the calculus; announced the three laws of motion which have become the basis of the science of mechanics; made important discoveries in light; is the author of the celebrated "Principia" (Principles of Natural Philosophy), published in 1687



THE CREAM SEPARATOR (1)

The milk is poured into a central opening at the top of a nest of disks (see 2) within a steel bowl The disks and bowl make from 6000 to 8000 revolutions per minute. The heavier parts of the milk (water, casein, and sugar) are thrown outward by centrifugal force against the lower surfaces of the disks (see 3) and then pass downward and outward to the periphery of the bowl. The lighter part (the cream) passes inward toward the upper surfaces of the disks (see 3), along which it flows upward to a series of openings near the center

a second, it follows that in this case *the momentums produced in the two bodies by the two forces are exactly proportional to the forces themselves.* In all cases in which forces simply overcome inertias this rule is found to hold. Thus, a 3000-pound pull on an automobile on a level road, where friction may be neglected, imparts in a second just twice as much velocity as does a 1500-pound pull. In view of this relation Newton's second law of motion was stated thus: *Rate of change of momentum is proportional to the force acting, and the change takes place in the direction in which the force acts.*

103. The third law. When a man jumps from a boat to the shore, we all know that the boat experiences a backward thrust; when a bullet is shot from a gun, the gun recoils, or "kicks"; when a billiard ball strikes another, it loses speed, that is, is pushed back while the second ball is pushed forward. The following experiment will show how effects of this sort may be studied quantitatively.

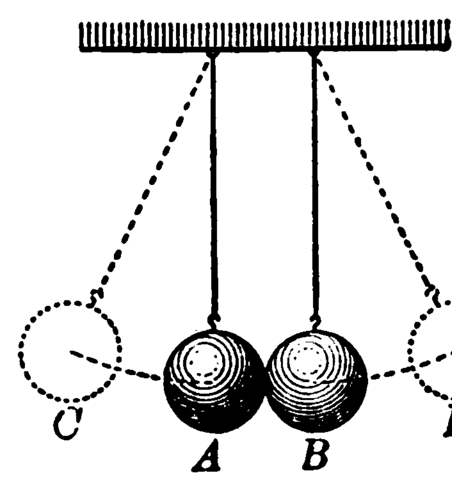


Fig. 86. Illustration of third law

Let a steel ball A (Fig. 86) be allowed to fall from a position C against another exactly similar ball B. In the impact A will lose practically all of its velocity, and B will move to a position D, which is at the same height as C. Hence the velocity acquired by B is almost exactly equal to that which A had before impact. These velocities would be exactly equal if the balls were perfectly elastic. It is found to be true experimentally that the momentum acquired by B plus that retained by A is exactly equal to the momentum which A had before the impact. The momentum acquired by B is therefore exactly equal to that lost by A. Since, by the second law, change in momentum is proportional to the force acting, this experiment shows that A pushed forward on B with precisely the same force with which B pushed back on A.

Now the essence of Newton's third law is the assertion that in the case of the man jumping from the boat the mass

of the man times his velocity is equal to the mass of the boat times its velocity, and that in the case of the bullet and gun the mass of the bullet times its velocity is equal to the mass of the gun times its velocity. The truth of this assertion has been established by a great variety of experiments.

Newton stated his third law thus: *To every action there is an equal and opposite reaction.*

Since force is measured by the rate at which momentum changes, this is only another way of saying that *whenever a body acquires momentum some other body acquires an equal and opposite momentum.*

It is not always easy to see at first that setting one body into motion involves imparting an equal and opposite momentum to another body. For example, when a gun is held against the earth and a bullet shot upward, we are conscious only of the motion of the bullet; the other body is in this case the earth, and its momentum is the same as that of the bullet. On account of the greatness of the earth's mass, however, its velocity is infinitesimal.

104. The dyne. Since the gram of force varies somewhat with locality, it has been found convenient for scientific purposes to take the second law as the basis for the definition of a new unit of force. It is called an absolute, or C.G.S., unit because it is based upon the fundamental units of length, mass, and time, and is therefore independent of gravity. It is named the *dyne* and is defined as *the force which, acting for one second upon any mass, imparts to it one unit of momentum;* or *the force which, acting for one second upon a one-gram mass, produces a* **change** *in its velocity of one centimeter per second.*

105. A gram of force equivalent to 980 dynes. A gram of force was defined as the pull of the earth upon 1 gram of mass. Since this pull is capable of imparting to this mass in 1 second a velocity of 980 centimeters per second, that is, 980 units of momentum, and since a dyne is the force required to impart in 1 second 1 unit of momentum, it is clear that the gram of force is equivalent to 980 dynes of force. The dyne is therefore a very small unit, about equal to the force with which the earth attracts a cubic millimeter of water.

106. Algebraic statement of the second law. If a force F acts for t seconds on a mass of m grams, and in so doing increases its velocity v centimeters per second, then, since the total momentum imparted in a time t is mv, the momentum imparted per second is $\frac{mv}{t}$; and since force in dynes is equal to momentum imparted per second, we have

$$F = \frac{mv}{t}. \tag{8}$$

But since $\frac{v}{t}$ is the velocity gained per second, it is equal to the acceleration a. Equation (8) may therefore be written

$$F = ma. \tag{9}$$

This is merely stating in the form of an equation that force is measured by rate of change of momentum. Thus, if an engine, after pulling for 30 sec. on a train having a mass of 2,000,000 kg., has given it a velocity of 60 cm. per second, the force of the pull is $2{,}000{,}000{,}000 \times \frac{60}{80} =$ 4,000,000,000 dynes. To reduce this force to grams we divide by 980, and to reduce it to kilos we divide further by 1000. Hence the pull exerted by the engine on the train $= \frac{4{,}000{,}000{,}000}{980{,}000} =$ 4081 kg., or 4.081 metric tons.

QUESTIONS AND PROBLEMS

1. What principle is applied when one tightens the head of a hammer by pounding on the handle?

2. Why does not the car C of Fig. 87 fall? What carries it from B to D?

3. Why does a flywheel cause machinery to run more steadily?

4. Balance a calling card on the finger and place a coin upon it. Snap out the card, leaving the coin balanced on the finger. What principle is illustrated?

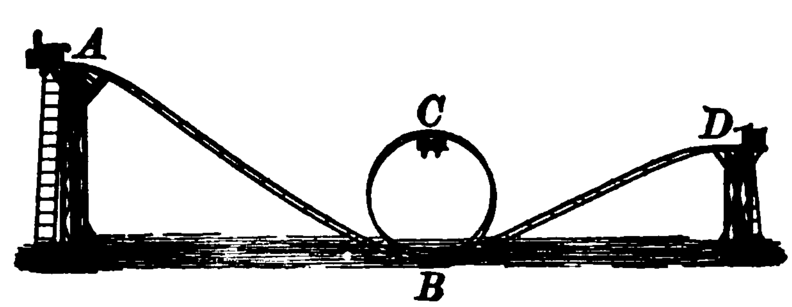


FIG. 87. A very ancient loop the loops

5. Is it any easier to walk toward the rear than toward the front of a rapidly moving train? Why?

6. Suspend a weight by a string. Attach a piece of the same string to the bottom of the weight. If the lower string is pulled with a sudden jerk, it breaks; but if the pull is steady, the upper string will break. Explain.

7. Where does a body weigh the more, at the poles or at the equator? Give two reasons.

8. If the trains A, B, and C (Fig. 88) are all running 60 mi. per hour, what is the velocity of A with reference to B? to C?

9. If a weight is dropped from the roof to the floor of a moving car, will it strike the point on the floor which was directly beneath its starting point?

Fig. 88

10. Why is a running track banked at the turns?

11. If the earth were to cease rotating, would bodies on the equator weigh more or less than now? Why?

12. How is the third law involved in rotary lawn sprinklers?

13. The modern way of drying clothes is to place them in a large cylinder with holes in the sides, and then to set it in rapid rotation. Explain.

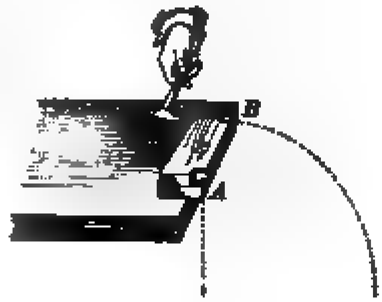


Fig. 89. Illustrating Newton's second law

14. Explain how reaction pushes the ocean liner and the airplane forward.

15. If one ball is thrown horizontally from the top of a tower and another dropped at the same instant, which will strike the earth first? (Remember that the acceleration produced by a force is in the direction in which the force acts and proportional to it, whether the body is at rest or in motion. See second law.) If possible, try the experiment with an arrangement like that of Fig. 89.

16. If a rifle bullet were fired horizontally from a tower 19.6 m. high with a speed of 300 m., how far from the base of the tower would it strike the earth if there were no air resistance?

Fig. 90. Hydraulic ram

17. The hydraulic ram (Fig. 90) is a practical illustration of the principle of inertia. With its aid water from a pond P can be raised

into a tank that stands at a higher level than the pond. With the aid of Fig. 91 explain how it works, remembering that the valve *V* will not close until the stream of water flowing around it acquires sufficient speed.

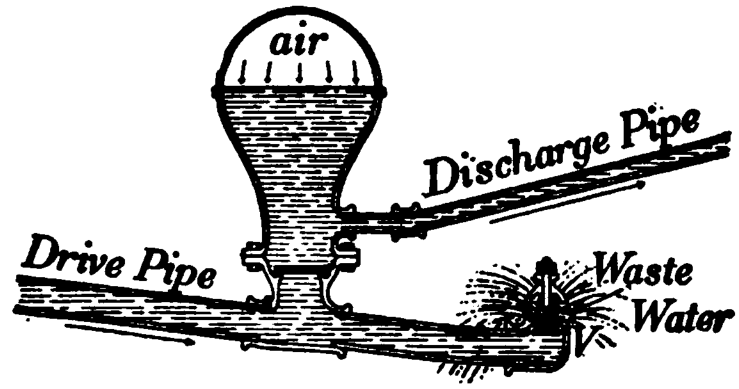


FIG. 91

18. If two men were together in the middle of a perfectly smooth (frictionless) pond of ice, how could they get off? Could one man get off if he were there alone?

19. If a 10-g. bullet is shot from a 5-kg. gun with a speed of 400 m. per second, what is the backward speed of the gun?

20. If a team of horses pulls 500 lb. in drawing a wagon, with what force does the wagon pull backward upon the team? Why do the wheels turn before the hoofs of the horses slide?

21. Why does a falling mass, on striking, exert a force in excess of its weight?

22. A pull of a dyne acts for 3 sec. on a mass of 1 g. What velocity does it impart?

23. How long must a force of 100 dynes act on a mass of 20 g. to impart to it a velocity of 40 cm. per second?

24. A force of 1 dyne acts on 1 g. for 1 sec. How far has the gram been moved at the end of the second?

A laboratory exercise on the composition of forces should be performed during the study of this chapter See, for example, Experiment 11 of the authors' Manual.

CHAPTER VI

MOLECULAR FORCES *

MOLECULAR FORCES IN SOLIDS. ELASTICITY

107. That the molecules of solids cling together with forces of great magnitude is proved by some of the simplest facts of nature; for solids not only do not expand indefinitely like gases, but it often requires enormous forces to pull their molecules apart. Thus, a rod of cast steel 1 centimeter in diameter may be loaded with a weight of 7.8 tons before it will be pulled in two.

The following are the weights in kilograms necessary to break drawn wires of different materials, 1 square millimeter in cross section,—the so-called relative *tenacities* of the wires.

Lead, 2.6	Platinum, 43	Iron, 77
Silver, 37	Copper, 51	Steel, 91

108. Elasticity. We can obtain additional information about the molecular forces existing in different substances by studying what happens when the weights applied are not large enough to break the wires.

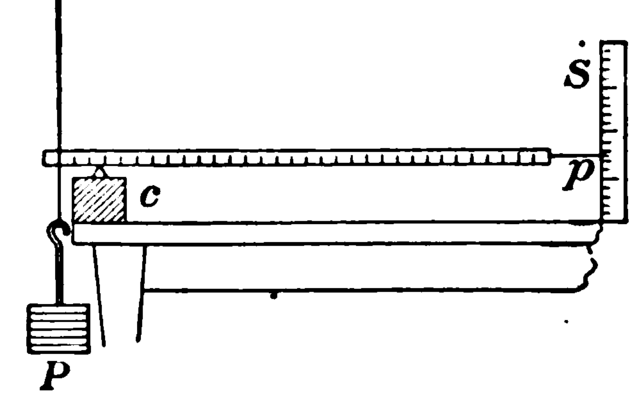


FIG. 92. Elasticity of a steel wire

Thus, let a long steel wire (for example, No. 26 piano wire) be suspended from a hook in the ceiling, and let the

* This chapter should be preceded by a laboratory experiment in which Hooke's law is discovered by the pupil for certain kinds of deformation easily measured in the laboratory. See, for example, Experiment 13 of the authors' Manual.

lower end be wrapped tightly about one end of a meter stick, as in Fig. 92. Let a fulcrum *c* be placed in a notch in the stick at a distance of about 5 cm. from the point of attachment to the wire, and let the other end of the stick be provided with a knitting needle, one end of which is opposite the vertical mirror scale *S*. Let enough weights be applied to the pan *P* to place the wire under slight tension; then let the reading of the pointer *p* on the scale *S* be taken. Let three or four kilogram weights be added successively to the pan and the corresponding positions of the pointer read. Then let the readings be taken again as the weights are successively removed. In this last operation the pointer will probably be found to come back exactly to its first position.

This characteristic which the steel has shown in this experiment, of returning to its original length when the stretching weights are removed, is an illustration of a property possessed to a greater or less extent by all solid bodies. It is called *elasticity.*

109. Limits of perfect elasticity. If a sufficiently large weight is applied to the end of the wire of Fig. 92, it will be found that the pointer does not return exactly to its original position when the weight is removed. We say, therefore, that steel is *perfectly elastic* only so long as the distorting forces are kept within certain limits, and that as soon as these limits are overstepped it no longer shows perfect elasticity. Different substances differ very greatly in the amount of distortion which they can sustain before they show this failure to return completely to the original shape.

110. Hooke's law. If we examine the stretches produced by the successive addition of kilogram weights in the experiment of § 108, Fig. 92, we shall find that these stretches are all equal, at least within the limits of observational error. Very carefully conducted experiments have shown that this law, namely, that the successive application of equal forces produces a succession of equal stretches, holds very exactly for all sorts of elastic displacements so long, and only so long, as the limits of perfect elasticity are not overstepped. This

law is known as Hooke's law, after the Englishman Robert Hooke (1635–1703). Another way of stating this law is the following: *Within the limits of perfect elasticity elastic deformations of any sort, be they twists or bends or stretches, are directly proportional to the forces producing them.* The common spring balance (Fig. 57) is an application of Hooke's law.

111. Cohesion and adhesion. The preceding experiments have brought out the fact that, in the solid condition at least, molecules of the same kind exert attractive forces upon one another. That molecules of unlike substances also exert mutually attractive forces is equally true, as is proved by the fact that glue sticks to wood with tremendous tenacity, mortar to bricks, nickel plating to iron, etc.

The forces which bind *like* kinds of molecules together are commonly called *cohesive forces;* those which bind together molecules of *unlike* kind are called *adhesive forces.* Thus, we say that mucilage sticks to wood because of *adhesion,* while wood itself holds together because of *cohesion.* Again, adhesion holds the chalk to the blackboard, while cohesion holds together the particles of the crayon.

112. Properties of solids depending on cohesion. Many of the physical properties in which solid substances differ from one another depend on differences in the cohesive forces existing between their molecules. Thus, we are accustomed to classify solids with relation to their hardness, brittleness, ductility, malleability, tenacity, elasticity, etc. The last two of these terms have been sufficiently explained in the preceding paragraphs; but since confusion sometimes arises from failure to understand the first four, the tests for these properties are here given.

We test the relative *hardness* of two bodies by seeing which will *scratch* the other. Thus, the diamond is the hardest of all substances, since it scratches all others and is scratched by none of them.

We test the relative *brittleness* of two substances by seeing which will *break* the more easily under a blow from a hammer. Thus, glass and ice are very brittle substances; lead and copper are not.

We test the relative *ductility* of two bodies by seeing which can be *drawn into the thinner wire.* Platinum is the most ductile of all substances. It has been drawn into wires only .00003 inch in diameter. Glass is also very ductile when sufficiently hot, as may be readily shown by heating it to softness in a Bunsen flame, when it may be drawn into threads which are so fine as to be almost invisible.

We test the relative *malleability* of two substances by seeing which can be *hammered into the thinner sheet.* Gold, the most malleable of all substances, has been hammered into sheets $\frac{1}{300000}$ inch in thickness.

QUESTIONS AND PROBLEMS

1. Tell how you may, by use of Hooke's law and a 20-lb. weight, make the scale for a 32-lb. spring balance.
2. A broken piece of wrought iron or steel may be welded by heating the broken ends white hot and pounding them together. Gold foil is welded cold in the process of filling a tooth. Explain welding.
3. A piece of broken wood may be mended with glue. What does the glue do?
4. Why are springs made of steel rather than of copper?
5. If a given weight is required to break a given wire, how much force is required to break two such wires hanging side by side? to break one wire of twice the diameter?

Molecular Forces in Liquids. Capillary Phenomena

113. Proof of the existence of molecular forces in liquids. The facility with which liquids change their shape might lead us to suspect that the molecules of such substances exert almost no force upon one another, but a simple experiment will show that this is far from true.

By means of sealing wax and string let a glass plate be suspended horizontally from one arm of a balance, as in Fig. 93. After equilibrium is obtained, let a surface of water be placed just beneath the plate and the beam pushed down until contact is made. It will be found necessary to add a considerable weight to the opposite pan in order to pull the plate away from the water. Since a layer of water will be found to cling to the glass, it is evident that the added force applied to the pan has been expended in pulling water molecules away from water molecules, not in pulling glass away from water. Similar experiments may be performed with all liquids. In the case of mercury the glass will not be found to be wet, showing that the cohesion of mercury is greater than the adhesion of glass and mercury.

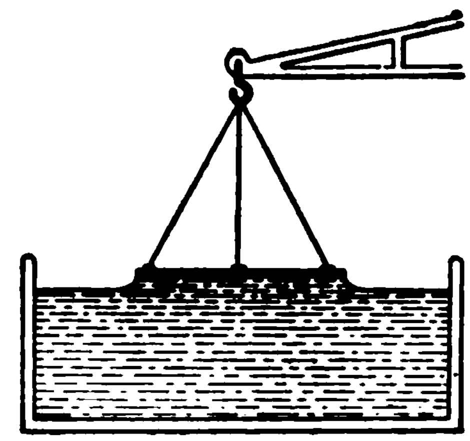


FIG. 93. Illustrating cohesion of water

114. Shape assumed by a free liquid. Since, then, every molecule of a liquid is pulling on every other molecule, any body of liquid which is free to take its natural shape, that is, which is acted on only by its own cohesive forces, must draw itself together until it has the smallest possible surface compatible with its volume; for, since every molecule in the surface is drawn toward the interior by the attraction of the molecules within, it is clear that molecules must continually move toward the center of the mass until the whole has reached the most compact form possible. Now the geometrical figure which has the smallest area for a given volume is a sphere. We conclude, therefore, that if we could relieve a body of liquid from the action of gravity and other outside forces, it would at once take the form of a perfect sphere. This conclusion may be easily verified by the following experiment:

Let alcohol be added to water until a solution is obtained in which a drop of common lubricating oil will float at any depth. Then with a pipette insert a large globule of oil beneath the surface. The oil will be seen to float as a perfect sphere within the body of the liquid (Fig. 94). (Unless the drop is viewed from above, the vessel should have flat rather

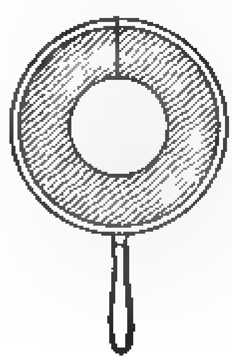
than cylindrical sides, otherwise the curved surface of the water will act like a lens and make the drop *appear* flattened.)

The reason that liquids are not more commonly observed to take the spherical form is that ordinarily the force of gravity is so large as to be more influential in determining their shape than are the cohesive forces. As verification of this statement we have only to observe that as a body of liquid becomes smaller and smaller — that is, as the gravitational forces upon it become less and less — it does indeed tend more and more to take the spherical form. Thus, very small globules of mercury on a table will be found to be almost perfect spheres, and raindrops or minute *floating* particles of all liquids are quite accurately spherical.

FIG. 94. Spherical globule of oil, freed from action of gravity

115. Contractility of liquid films; surface tension. The tendency of liquids to assume the smallest possible surface furnishes a simple explanation of the contractility of liquid films.

Let a soap bubble 2 or 3 inches in diameter be blown on the bowl of a pipe and then allowed to stand. It will at once begin to shrink in size and in a few minutes will disappear within the bowl of the pipe.



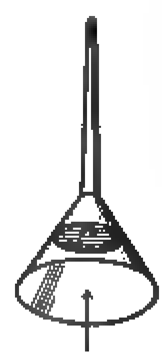


FIG. 95 FIG. 96 FIG. 97

Illustrating the contractility of soap films

The liquid of the bubble is simply obeying the tendency to reduce its surface to a minimum, a tendency which is due only to the mutual attractions which its molecules exert upon one another. A candle flame

held opposite the opening in the stem of the pipe will be deflected by the current of air which the contracting bubble is forcing out through the stem.

Again, let a loop of fine thread be tied to a wire ring, as in Fig. 95. Let the ring be dipped into a soap solution so as to form a film across it, and then let a hot wire be thrust through the film inside the loop. The tendency of the film outside the loop to contract will instantly snap out the thread into a perfect circle (Fig. 96). The reason that the thread takes the circular form is that, since the film outside the loop is striving to assume the smallest possible surface, the area inside the loop must of course become as large as possible. The circle is the figure which has the largest possible area for a given perimeter.

Let a soap film be formed across the mouth of a clean 2-inch funnel, as in Fig. 97. The tendency of the film to contract will be sufficient to lift its weight against the force of gravity.

The tendency of a liquid to reduce its exposed surface to a minimum, that is, *the tendency of any liquid surface to act like a stretched elastic membrane*, is called *surface tension*. The elastic nature of a film is illustrated in Fig. 98, which is from a motion-picture record of some of the stages through which a slowly forming drop passes.

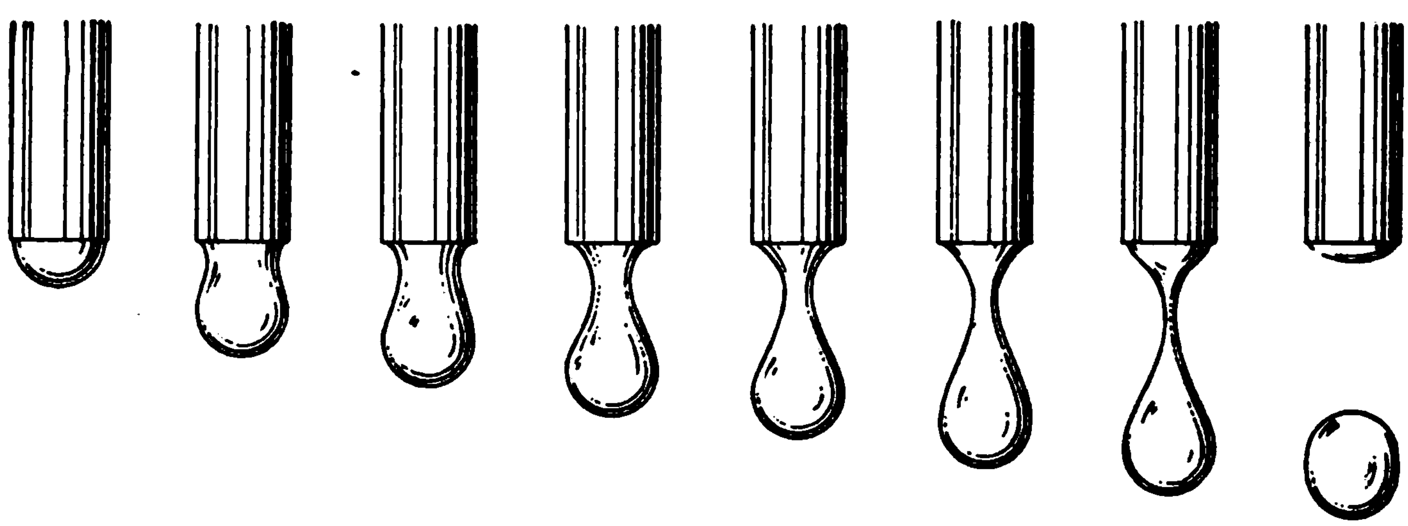


Fig. 98. Some of the stages through which a slowly forming drop passes

116. Ascension and depression of liquids in capillary tubes. It was shown in Chapter II that, in general, a liquid stands at the same level in any number of communicating vessels. The following experiments will show that this rule ceases to hold in the case of tubes of small diameter.

Let a series of capillary tubes of diameter varying from 2 mm. to .1 mm. be arranged as in Fig. 99.

When water or ink is poured into the vessel it will be found to rise higher in the tubes than in the vessel, and it will be seen that the smaller the tube the greater the height to which it rises. If the water is replaced by mercury, however, the effects will be found to be just inverted. The mercury is depressed in all the tubes, the depression being greater in proportion as the tube is smaller (Fig. 100, (1)). This depression is most easily observed with a U-tube like that shown in Fig. 100, (2).

Experiments of this sort have established the following laws:

Fig. 99. Rise of liquids in capillary tubes

1. *Liquids rise in capillary tubes when they are capable of wetting them, but are depressed in tubes which they do not wet.*

2. *The elevation in the one case and the depression in the other are inversely proportional to the diameters of the tubes.*

It will be noticed, too, that when a liquid rises, its surface within the tube is concave upward, and when it is depressed its surface is convex upward.

(2)

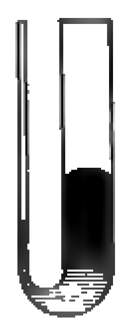


Fig. 100. Depression of mercury in capillary tubes

117. Cause of curvature of a liquid surface in a capillary tube. All of the effects presented in the last paragraph can be explained by a consideration of cohesive and adhesive forces. However, throughout the explanation we must keep in mind two familiar facts: first, that *the surface of a body of water at rest, for example a pond, is at right angles to the resultant force, that is, gravity, which acts upon it;* and, second, that *the force of gravity acting on a minute amount of liquid is negligible in comparison with its own cohesive force* (see § 114).

Consider, then, a very small body of liquid close to the point *o* (Fig. 101), where water is in contact with the glass wall of the tube. Let the quantity of liquid considered be so minute that the force of gravity acting upon it may be disregarded. The force of *adhesion* of the wall will pull the liquid particles at *o* in the direction *oE*. The force of *cohesion* of the liquid will pull these same particles in the direction *oF*. The resultant of these two pulls on the liquid at *o* will then be represented by *oR* (Fig. 101), in accordance with the parallelogram law of Chapter V. If, then, the resultant *oR* of the adhesive force *oE* and the cohesive force *oF* lies to the left of the vertical *om* (Fig. 102), since the surface of a liquid always assumes a position at right angles to the resultant force, the liquid must rise up against the wall as water does against glass (Fig. 102).

Fig. 101 Fig. 102

Condition for elevation of a liquid near a wall

If the cohesive force *oF* (Fig. 103) is strong in comparison with the adhesive force *oE*, the resultant *oR* will fall to the right of the vertical, in which case the liquid must be depressed about *o*.

Fig. 103. Condition for the depression of a liquid near a wall

Whether, then, a liquid will rise against a solid wall or be depressed by it will depend only on the relative strengths of the adhesion of the wall for the liquid and the cohesion of the liquid for itself. Since mercury does not wet glass, we know that cohesion is here relatively strong, and we should expect, therefore, that the mercury

would be depressed, as indeed we find it to be. The fact that water will wet glass indicates that in this case adhesion is relatively strong, and hence we should expect water to rise against the walls of the containing vessel, as in fact it does.

It is clear that a liquid which is depressed near the edge of a vertical solid wall must assume within a tube a surface which is *convex upward*, while a liquid which rises against a wall must within such a tube be *concave upward*.

118. Explanation of ascension and depression in capillary tubes. As soon as the curvatures just mentioned are produced, the concave surface *aob* (Fig. 104) tends, by virtue of

FIG. 104 FIG. 105

A concave meniscus causes a rise in a capillary tube

FIG. 106 FIG. 107

A convex meniscus causes a fall

surface tension, to straighten out into the flat surface *ao′b*. But it no sooner thus begins to straighten out than adhesion again elevates it at the edges. It will be seen, therefore, that the liquid must continue to rise in the tube until the weight of the volume of liquid lifted, namely *amnb* (Fig. 105), balances the tendency of the surface *aob* to flatten out. That the liquid will rise higher in a small tube than in a large one is to be expected, since the weight of the column of liquid to be supported in the small tube is less.

The convex mercury surface *aob* (Fig. 106) falls until the upward pressure at *o*, due to the depth *h* of mercury (Fig. 107), balances the tendency of the surface *aob* to flatten.

119. Capillary phenomena in everyday life. Capillary phenomena play a very important part in the processes of nature and of everyday life. Thus the rise of oil in wicks of lamps, the complete wetting of a towel when one end of it is allowed to stand in a basin of water, the rapid absorption of liquid by a lump of sugar when one corner of it only is immersed, the taking up of ink by blotting paper, are all illustrations of precisely the same phenomena which we observe in the capillary tubes of Fig. 99.

120. Floating of small objects on water. Let a needle be laid very carefully on the surface of a dish of water. In spite of the fact that it is nearly eight times as dense as water it will be found to float. If the needle has been previously magnetized, it may be made to move about in any direction over the surface in obedience to the pull of a magnet held, for example, underneath the table.

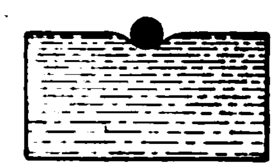


FIG. 108. Cross section of a floating needle

To discover the cause of this apparently impossible phenomenon, examine closely the surface of the water in the immediate neighborhood of the needle. It will be found to be depressed in the manner shown in Fig. 108. This furnishes at once the explanation. So long as the needle is so small that its own weight is no greater than the upward force exerted upon it by the tendency of the depressed (and therefore concave) liquid surface to straighten out into a flat surface, the needle cannot sink in the liquid, no matter how great its density. If the water had wet the needle, that is, if it had risen about the needle instead of being depressed, the tendency of the liquid surface to flatten out would have pulled it down into the liquid instead of forcing it upward. Any body about which a liquid is depressed will therefore float on the surface of the liquid if its mass is not too great. Even if the liquid

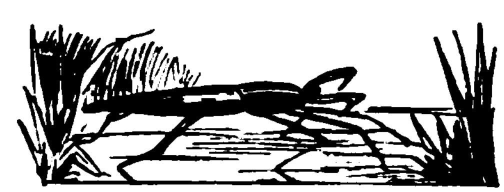


FIG. 109. Insect walking on the surface of water

tends to rise about a body when it is perfectly clean, an imperceptible film of oil upon the body will cause it to depress the liquid, and hence to float.

The above experiment explains the familiar phenomenon of insects walking and running on the surface of water (Fig. 109) in apparent contradiction to the law of Archimedes, in accordance with which they should sink until they displace their own weight of the liquid.

QUESTIONS AND PROBLEMS

1. Explain how capillary attraction comes usefully into play in the steel pen, camel's-hair brushes, lamp wicks, and sponges.

2. Candle grease may be removed from clothing by covering it with blotting paper and then passing a hot flatiron over the paper. Explain.

3. Why will a piece of sharp-cornered glass become rounded when heated to redness in a Bunsen flame?

4. The leads for pencils are made by subjecting powdered graphite to enormous pressures produced by hydraulic machines. Explain how the pressure changes the powder to a coherent mass.

5. Float two matches an inch apart. Touch the water between them with a hot wire. The matches will spring apart. What does this show about the effect of temperature on surface tension?

6. Repeat the experiment, touching the water with a wire moistened with alcohol. What do you infer as to the relative surface tensions of alcohol and water?

7. Fasten a bit of gum camphor to one end of half a toothpick and lay it upon the surface of a large vessel of clean still water. Explain the motion.

8. Shot are made by pouring molten lead through a sieve on top of a tall tower and catching it in water at the bottom. Why are the shot spherical?

9. Explain how capillary attraction makes an irrigation system successful.

10. In building a macadam road coarse stones are placed at the bottom, on top of them smaller stones, and finally little granules tightly rolled together by means of a steam roller. Explain how this arrangement of material keeps the road dry.

11. What force is mainly responsible for the return of the water that has gravitated into the soil? Would the looseness of the soil make any difference (dry farming)?

Absorption of Gases by Solids and Liquids

121. Absorption of gases by solids. Let a large test tube be filled with ammonia gas by heating aqua ammonia and causing the evolved gas to displace mercury in the tube, as in Fig. 110. Let a piece of charcoal an inch long and nearly as wide as the tube be heated to redness and then plunged beneath the mercury. When it is cool, let it be slipped underneath the mouth of the test tube and allowed to rise into the gas. The mercury will be seen to rise in the tube, as in Fig. 111. Why?

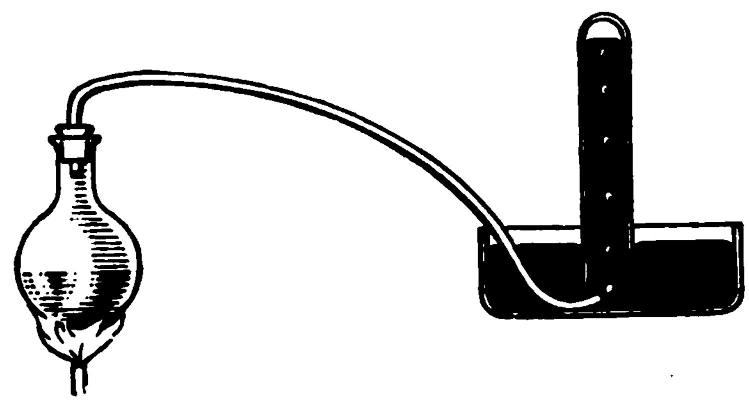


Fig. 110. Filling tube with ammonia

This property of absorbing gases is possessed to a notable degree by porous substances, especially coconut and peach-pit charcoal. It is not improbable that all solids hold, closely adhering to their surfaces, thin layers of the gases with which they are in contact, and that the prominence of the phenomena of absorption in porous substances is due to the great extent of surface possessed by such substances.

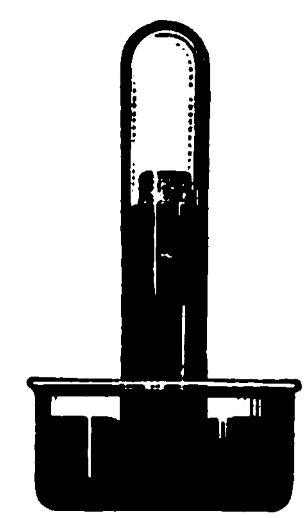


Fig. 111. Absorption of ammonia gas by charcoal

That the same substance exerts widely different attractions upon the molecules of different gases is shown by the fact that charcoal will absorb 90 times its own volume of ammonia gas, 35 times its volume of carbon dioxide, and only 1.7 times its volume of hydrogen. The usefulness of charcoal as a deodorizer is due to its enormous ability to absorb certain kinds of gases. This property made it available for use in gas masks (see opposite p. 103) during the World War. If a little spongy platinum is suspended in a vessel above wood alcohol, it will glow brightly because of the absorption into the platinum of both vapor of alcohol and oxygen. The rapid

James Clerk-Maxwell
(1831–1879)

One of the greatest of mathematical physicists, born in Edinburgh, Scotland; professor of natural philosophy at Marischal College, Aberdeen, in 1856, of physics and astronomy in Kings College, London, in 1860, and of experimental physics in Cambridge University from 1871 to 1879; one of the most prominent figures in the development of the kinetic theory of gases and the mechanical theory of heat; author of the electromagnetic theory of light — a theory which has become the basis of nearly all modern theoretical work in electricity and optics (see p. 426)

Heinrich Rudolph Hertz
(1857–1894)

One of the most brilliant of German physicists, who, in spite of his early death at the age of thirty-seven, made notable contributions to theoretical physics, and left behind the epoch-making experimental discovery of the electromagnetic waves predicted by Maxwell. Wireless telegraphy is but an application of this discovery of so-called "Hertzian" waves (see p. 422). The capital discovery that ultra-violet light discharges negatively electrified bodies is also due to Hertz

© U. S. Official

A Gas Mask

A great variety of poisonous gases having a density greater than air were set free and carried by the wind against the Allied armies in the World War, and others were fired in explosive shells. Until gas masks were devised these gases, settling into the trenches, wrought frightful havoc among the troops. The absorptive power of charcoal, especially when impregnated with certain chemicals, proved an effective barrier against the deadly fumes, since all of the air entering the lungs of the soldiers had to be inhaled through the charcoal within a canister carried in the bag designed to hold the gas mask. The illustration shows an American gas mask adjusted to the head of an American soldier

rise in temperature is due to the increased rate of oxidation of the alcohol brought about by this more intimate mixture. This property of platinum is utilized in the platinum-alcohol cigar lighter (Fig. 112).

122. Absorption of gases in liquids. Let a beaker containing cold water be slowly heated. Small bubbles of air will be seen to collect in great numbers upon the walls and to rise through the liquid to the surface. That they are indeed bubbles of air and not of steam is proved, first, by the fact that they appear when the temperature is far below boiling, and, second, by the fact that they do not condense as they rise into the higher and cooler layers of the water.

FIG. 112. The platinum-alcohol cigar lighter

The experiment shows two things: first, that water ordinarily contains considerable quantities of air dissolved in it; and, second, that the amount of air which water can hold decreases as the temperature rises. The first point is also proved by the existence of fish life; for fishes obtain the oxygen which they need to support life from air which is dissolved in the water.

The amount of gas which will be absorbed by water varies greatly with the nature of the gas. At 0° C. and a pressure of 76 centimeters 1 cubic centimeter of water will absorb 1050 cubic centimeters of ammonia, 1.8 cubic centimeters of carbon dioxide, and only .04 cubic centimeter of oxygen. Commercial aqua ammonia is simply ammonia gas dissolved in water.

The following experiment illustrates the absorption of ammonia by water:

Let the flask *F* (Fig. 113) and tube *b* be filled with ammonia by passing a current of the gas in at *a* and out through *b*. Then let *a* be corked up and *b* thrust into *G*, a flask nearly filled with water which has been colored slightly red by the addition of litmus and a drop or two of acid. As the ammonia is absorbed the water will slowly rise in *b*, and as soon

as it reaches F it will rush up very rapidly until the upper flask is nearly full. At the same time the color will change from red to blue because of the action of the ammonia upon the litmus.

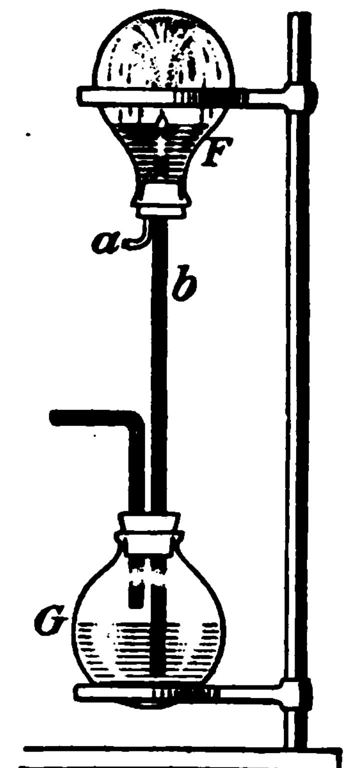


FIG. 113. Absorption of ammonia by water

Experiment shows that *in every case of absorption of a gas by a liquid or a solid the quantity of gas absorbed decreases with an increase in temperature,* — a result which was to have been expected from the kinetic theory, since increasing the molecular velocity must of course increase the difficulty which the adhesive forces have in retaining the gaseous molecules.

123. Effect of pressure upon absorption. Soda water is ordinary water which has been made to absorb large quantities of carbon dioxide gas. This impregnation is accomplished by bringing the water into contact with the gas under high pressure. As soon as the pressure is relieved, the gas passes rapidly out of solution. This is the cause of the characteristic effervescence of soda water. These facts show clearly that the amount of carbon dioxide which can be absorbed by water is greater for high pressures than for low. As a matter of fact, careful experiments have shown that the amount of any gas absorbed is directly proportional to the pressure, so that if carbon dioxide under a pressure of 10 atmospheres is brought into contact with water, ten times as much of the gas is absorbed as if it had been under a pressure of 1 atmosphere. This is known as Henry's law.

QUESTIONS AND PROBLEMS

1. Why do fishes in an aquarium die if the water is not frequently renewed?

2. Explain the apparent generation of ammonia gas when aqua ammonia is heated.

3. Why, in the experiment illustrated in Fig. 113, was the flow so much more rapid after the water began to run over into F?

CHAPTER VII

WORK AND MECHANICAL ENERGY *

Definition and Measurement of Work

124. Definition of work. Whenever a force *moves* a body on which it acts, it is said to do work upon that body, and the amount of the work accomplished is measured by the product of the force acting and the distance through which it moves the body. Thus, if 1 gram of mass is lifted 1 centimeter in a vertical direction, 1 gram of force has acted, and the distance through which it has moved the body is 1 centimeter. We say, therefore, that the lifting force has accomplished 1 *gram centimeter* of work. If the gram of force had lifted the body upon which it acted through 2 centimeters, the work done would have been 2 gram centimeters. If a force of 3 grams had acted and the body had been lifted through 3 centimeters, the work done would have been 9 gram centimeters, etc. Or, in general, if W represent the work accomplished, F the value of the acting force, and s the distance through which its point of application moves, then the definition of work is given by the equation

$$W = F \times s. \tag{1}$$

In the scientific sense no work is ever done unless the force succeeds in *producing motion* in the body on which it

* It is recommended that this chapter be preceded by an experiment in which the student discovers for himself the law of the lever, that is, the principle of moments (see, for example, Experiment 16, authors' Manual), and that it be accompanied by a study of the principle of work as exemplified in at least one of the other simple machines (see, for example, Experiment 17, authors' Manual).

acts. A pillar supporting a building does no work; a man tugging at a stone, but failing to move it, does no work. In the popular sense we sometimes say that we are doing work when we are simply holding a weight or doing anything else which results in fatigue; but in physics the word "work" is used to describe not the effort put forth but the *effect accomplished*, as represented in equation (1).

125. Units of work. There are two common units of work in the metric system, the *gram centimeter* and the *kilogram meter*. As the names imply, the gram centimeter is the work done by a force of 1 gram when it moves the point on which it acts 1 centimeter. The kilogram meter is the work done by a kilogram of force when it moves the point on which it acts 1 meter. The *gram meter* also is sometimes used.

Corresponding to the English unit of force, the pound, is the unit of work, the *foot pound*. It is the work done by a "pound of force" when it moves the point on which it acts 1 foot. Thus, it takes a foot pound of work to lift a pound of mass 1 foot high.

In the absolute system of units the dyne is the unit of force, and the dyne centimeter, or *erg*, is the corresponding unit of work. The erg is the amount of work done by a force of 1 dyne when it moves the point on which it acts 1 centimeter. To raise 1 liter of water from the floor to a table 1 meter high would require $1000 \times 980 \times 100 = 98{,}000{,}000$ ergs of work. It will be seen, therefore, that the erg is an exceedingly small unit. For this reason it is customary to employ a unit which is equal to 10,000,000 ergs. It is called a *joule*, in honor of the great English physicist James Prescott Joule (1818–1889). The work done in lifting a liter of water 1 meter is therefore 9.8 joules.

QUESTIONS AND PROBLEMS

1. To drag a trunk weighing 120 lb. required a force of 40 lb. How much work would be required to drag this trunk 2 yd.? to lift it 2 yd. vertically?

2. A carpenter pushed 5 lb. on his plane while taking off a shaving 4 ft. long. How much work was done?

3. How many foot pounds of work does a 150-lb. man do in climbing to the top of Mt. Washington, which is 6300 ft. high?

4. A horse pulls a metric ton of coal to the top of a hill 30 m. high. Express the work accomplished in kilogram meters (a metric ton = 1000 kg.).

5. If the 20,000 inhabitants of a city use an average of 20 liters of water per capita per day, how many kilogram meters of work must the engines do per day if the water has to be raised to a height of 75 m.?

WORK EXPENDED UPON AND ACCOMPLISHED BY SYSTEMS OF PULLEYS

126. The single fixed pulley. Let the force of the earth's attraction upon a mass R be overcome by pulling upon a spring balance S, in the manner shown in Fig. 114, until R moves slowly upward. If R is 100 grams, the spring balance will also be found to register a force of 100 grams.

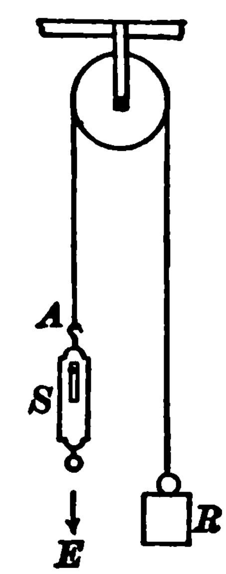


FIG. 114. The single fixed pulley

Experiment therefore shows that in the use of the single fixed pulley the acting force, or effort, E, which is producing the motion, is equal to the resisting force, or resistance, R, which is opposing the motion.

Again, since the length of the string is always constant, the distance s through which the point A, at which E is applied, must move is always equal to the distance s' through which the weight R is lifted. Hence, if we consider the work put into the system at A, namely, $E \times s$, and the work accomplished by the system at R, namely, $R \times s'$, we find, obviously, since $R = E$ and $s = s'$, that

$$E \times s = R \times s'; \tag{2}$$

that is, in the case of the single fixed pulley, *the work done by the acting force E (the effort) is equal to the work done against the resisting force R (the resistance)*, or the work *put into* the machine at A is equal to the work *accomplished by* the machine at R.

127. The single movable pulley. Now let the force of the earth's attraction upon the mass R be overcome by a single movable pulley, as shown in Fig. 115. Since the weight of R (R representing in this case the weight of both the pulley and the suspended mass) is now supported half by the strand C and half by the strand B, the force E which must act at A to hold the weight in place, or to move it slowly upward if there is no friction, should be only one half of R. A reading of the balance will show that this is indeed the case.

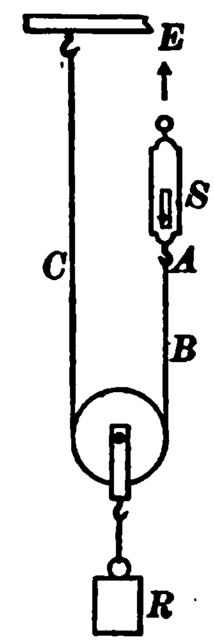


FIG. 115. The single movable pulley

Experiment thus shows that *in the case of the single movable pulley the effort E is just one half as great as the resistance R.*

But when we again consider the *work* which the force E must do to lift the weight R a distance s', we see that A must move upward 2 inches in order to raise R 1 inch; for when R moves up 1 inch, both of the strands B and C must be shortened 1 inch. As before, therefore, since $R = 2\ E$ and $s' = \frac{1}{2}\ s$,

$$E \times s = R \times s';$$

that is, in the case of the single movable pulley, as in the case of the fixed pulley, *the work put into the machine by the effort E is equal to the work accomplished by the machine against the resistance R.*

128. Combinations of pulleys. Let a weight R be lifted by means of such a system of pulleys as is shown in Fig. 116, either (1) or (2). Here, since R is supported by 6 strands of the cord, it is clear that the force which must be applied at A in order to hold R in place, or to make it move slowly upward if there is no friction, should be but $\frac{1}{6}$ of R.

The experiment will show this to be the case if the effects of friction, which are often very considerable, are eliminated by taking the mean of the forces which must be applied at E to cause it to move first slowly upward and then slowly downward. The law of any combination of movable pulleys may

then be stated thus: *If n represents the number of strands between which the weight is divided,*

$$E = R/n. \tag{3}$$

But when we again consider the work which the force E must do in order to lift the weight R through a distance s', we see that, in order that the weight R may be moved up through 1 inch, each of the strands must be shortened 1 inch, and hence the point A must move through n inches; that is, $s' = s/n$. Hence, ignoring friction, in this case also we have

$$E \times s = R \times s';$$

that is, although the effort E is only $\frac{1}{n}$ of the resistance R, *the work put into the machine by the effort E is equal to the work accomplished by the machine against the resistance R.*

(1) (2)

FIG. 116. Combinations of pulleys

129. Mechanical advantage. The above experiments show that it is sometimes possible by applying a small force E to overcome a much larger resisting force R. *The ratio of the resistance R to the effort E (ignoring friction) is called the mechanical advantage of the machine.* Thus, the mechanical advantage of the single fixed pulley is 1, that of the single movable pulley is 2, that of the system of pulleys shown in Fig. 116 is 6, etc.

If the acting force is applied at R instead of at E the mechanical advantage of the systems of pulleys of Fig. 116 is $\frac{1}{6}$; for it requires an application of 6 pounds at R to lift 1 pound at E. But it will be observed that the resisting force at E now moves six times as fast and six times as far as the acting force at R. We can thus either sacrifice speed to gain force, or

sacrifice force to gain speed; but in every case, whatever we gain in the one we lose in the other. Thus in the hydraulic elevator shown in Fig. 13, p. 18, the cage moves only as fast as the piston; but in that shown in Fig. 14 it moves four times as fast. Hence the force applied to the piston in the latter case must be four times as great as in the former if the same load is to be lifted. This means that the diameter of the latter cylinder must be twice as great.

QUESTIONS AND PROBLEMS

1. Although the mechanical advantage of the fixed pulley is only 1, it is extensively used in connection with clothes lines, awnings, open wells, and flags. Explain.

2. If the hydraulic elevator of Fig. 14, p. 18, is to carry a total load of 20,000 lb., what force must be applied to the piston? If the water pressure is 70 lb. per square inch, what must be the area of the piston?

3. Draw a diagram of a set of pulleys by which a force of 50 lb. can support a load of 200 lb.

4. Draw a diagram of a set of pulleys by which a force of 50 lb. can support 250 lb. What would be the mechanical advantage of this arrangement?

5. Two men, pulling 50 lb. each, lifted 300 lb. by a system of pulleys. Assuming no friction, how many feet of rope did they pull down in raising the weight 20 ft.?

WORK AND THE LEVER

130. The law of the lever. The lever is a rigid rod free to turn about some point P called the *fulcrum* (Fig. 117).

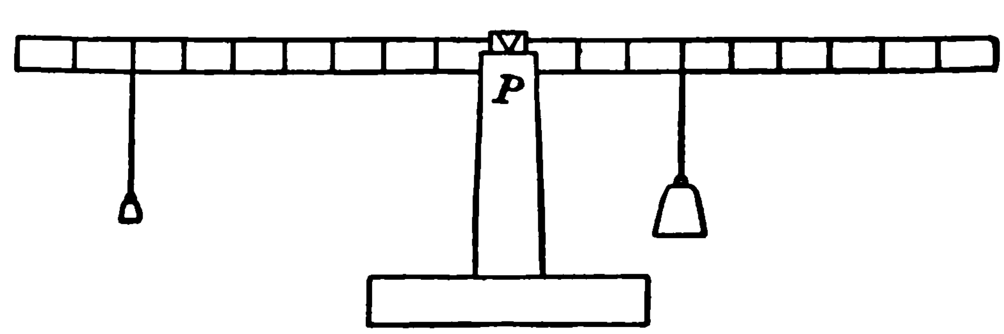


FIG. 117. The simple lever

First let a meter stick be balanced as in the figure, and then let a mass of, say, 300 g. be hung by a thread from a point 15 cm. from the fulcrum. Then let a point be found on the other side of the fulcrum at which a weight of 100 g. will just support the 300 g. This point will be found to be

45 cm. from the fulcrum. It will be seen at once that the product of 300 × 15 is equal to the product of 100 × 45.

Next let the point be found at which 150 g. just balance the 300 g. This will be found to be 30 cm. from the fulcrum. Again, the products 300 × 15 and 150 × 30 are equal.

No matter where the weights are placed, or what weights are used on either side of the fulcrum, the product of the effort E by its distance l from the fulcrum (Fig. 118) will be found to be equal to the product of the resistance R by its distance l' from the fulcrum. Now the perpendicular distances l and l' from the fulcrum to the line of action of the forces are called the *lever arms* of the forces E and R, and the product of a force by its lever arm is called the *moment* of that force. The above experiments on the lever may then be generalized in the following law: *The moment of the effort is equal to the moment of the resistance.* Algebraically stated, it is

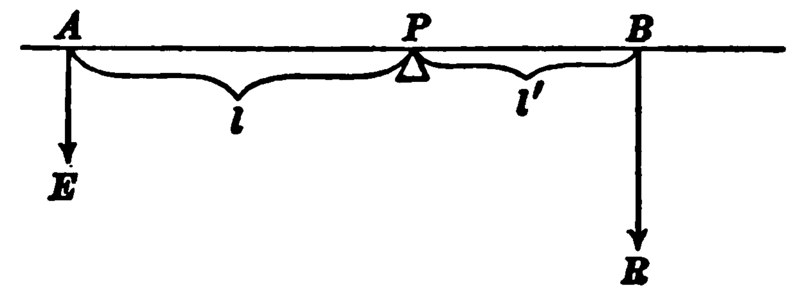


FIG. 118. Illustrating the law of moments, namely, $El = Rl'$

$$El = Rl'. \tag{4}$$

It will be seen that the *mechanical advantage* of the lever, namely R/E, is equal to l/l'; that is, *to the lever arm of the effort divided by the lever arm of the resistance.*

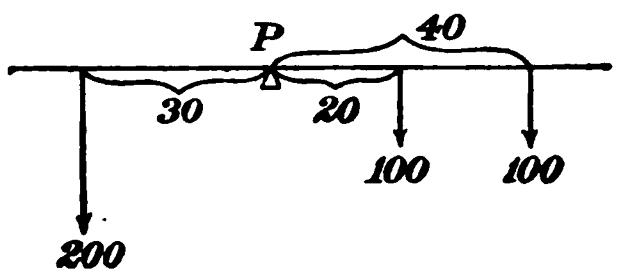
131. General laws of the lever. If parallel forces are applied at several points on a lever, as in Figs. 119 and 120, it will be found, in the particular cases illustrated, that for equilibrium

$$200 \times 30 = 100 \times 20 + 100 \times 40$$

and $$300 \times 20 + 50 \times 40 = 100 \times 15 + 200 \times 32.5;$$

that is, *the sum of all the moments which are tending to turn the beam in one direction is equal to the sum of all the moments tending to turn it in the opposite direction.*

If, further, we support the levers of Figs. 119 and 120 by spring balances attached at P, we shall find, after allowing for the weight of the stick, that the two forces indicated by the balances are respectively $200 + 100 + 100 = 400$ and $300 + 100 + 200 - 50 = 550$; that is, *the sum of all the forces acting in one direction on the lever is equal to the sum of all the forces acting in the opposite direction.*



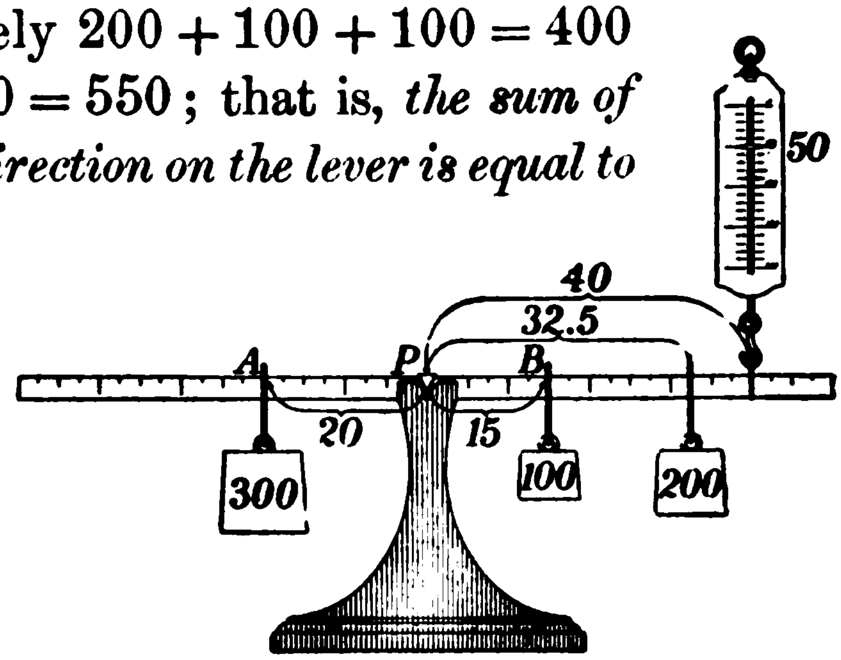


FIG. 119

FIG. 120

Condition of equilibrium of a bar acted upon by several forces

These two laws may be combined as follows: If we think of the force exerted by the spring balance as the equilibrant of all the other forces acting on the lever, then we find that *the resultant of any number of parallel forces is their algebraic sum, and its point of application is the point about which the algebraic sum of the moments is zero.*

132. The couple. There is one case, however, in which parallel forces can have no single force as their resultant, namely, the case represented in Fig. 121. Such *a pair of equal and opposite forces acting at different points on a lever is called a couple* and can be neutralized only by another couple tending to produce rotation in the opposite direction. The moment of such a couple is evidently $F_1 \times oa + F_2 \times ob = F_1 \times ab$; that is, it is one of the forces times the total distance between them. The forces applied to the steering wheel of an automobile illustrate the couple.

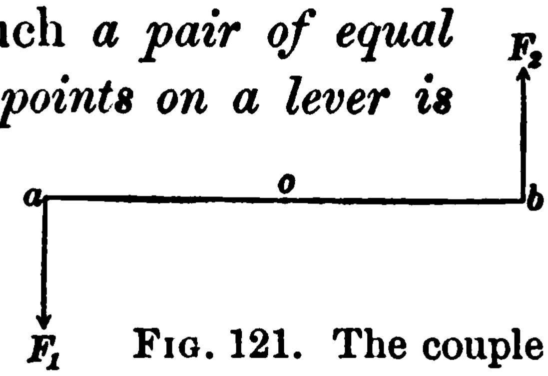


FIG. 121. The couple

133. Work expended upon and accomplished by the lever. We have just seen that when the lever is in equilibrium — that is, when it is *at rest* or is *moving uniformly* — the relation between the effort E and the resistance R is expressed in the equation of moments, namely $El = Rl'$. Let us now suppose, precisely as in the case of the pulleys, that the force E raises the weight R through a small distance s'. To accomplish this, the point A to which E is attached must move through a distance s (Fig. 122). From the similarity of the triangles APn and BPm it will be seen that l/l' is equal to s/s'. Hence equation (4), which represents the law of the lever, and which may be written $E/R = l'/l$, may also be written in the form

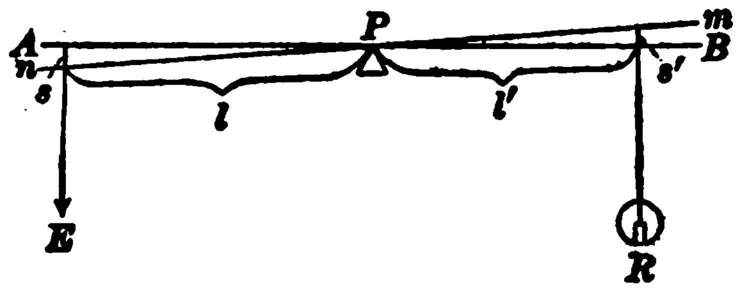


FIG. 122. Showing that the equation of moments, $El = Rl'$, is equivalent to $Es = Rs'$

$$E/R = s'/s, \text{ or } Es = Rs'.$$

Now Es represents the work done by the effort E, and Rs' the work done against the resistance R. Hence the law of moments, which has just been found by experiment to be the law of the lever, is equivalent to the statement that *whenever work is accomplished by the use of the lever, the work expended upon the lever by the effort E is equal to the work accomplished by the lever against the resistance R.*

134. The three classes of levers. Although the law stated in § 133 applies to all forms of the lever, it is customary to divide them into three classes, as follows:

1. In levers of the first class the fulcrum P is between the acting force E and the resisting force R (Fig. 123). The mechanical advantage of levers of this class is greater or less than unity according as the lever arm l of the effort is greater or less than the lever arm l' of the resistance.

2. In levers of the second class the resistance *R* is between the effort *E* and the fulcrum *P* (Fig. 124). Here the lever arm of the effort, that is, the distance from *E* to *P*, is necessarily greater than the lever arm of the resistance, that is, the

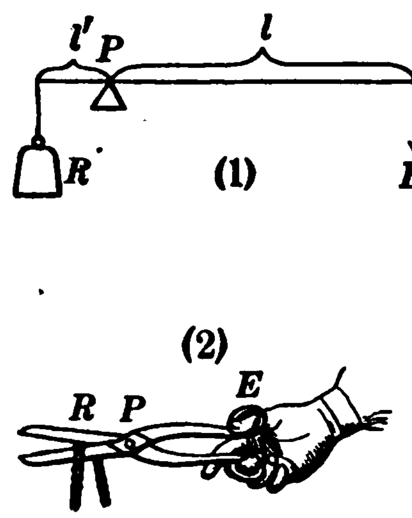


FIG. 123. Levers of first class

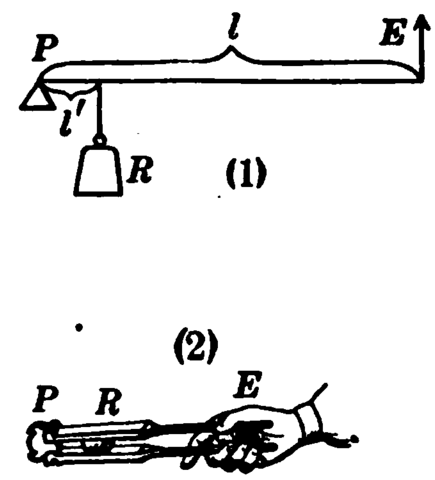


FIG. 124. Levers of second class

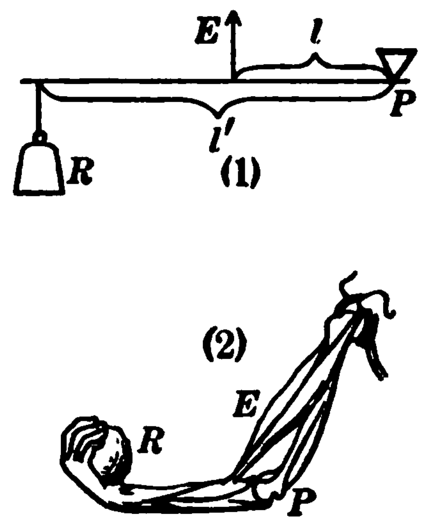


FIG. 125. Levers of third class

distance from *R* to *P*. Hence the mechanical advantage of levers of the second class is always greater than 1.

3. In levers of the third class the acting force is between the resisting force and the fulcrum (Fig. 125). The mechanical advantage is then obviously less than 1, that is, in this type of lever force is always sacrificed for the sake of gaining speed.

QUESTIONS AND PROBLEMS

1. In which of the three classes of levers does the wheelbarrow belong? grocer's scales? pliers? sugar tongs? a claw hammer? a pump handle?

2. Explain the principle of weighing by the steelyards (Fig. 126). What must be the weight of the bob *P* if at a distance of 40 cm. from the fulcrum *O* it balances a weight of 10 kg. placed at a distance of 2 cm. from *O*?

3. If you knew your own weight, how could you determine the weight of a companion if you had only a teeter board and a foot rule?

4. How would you arrange a crowbar to use it as a lever of the first class in overturning a heavy object? as a lever of the second class?

5. Why do tinners' shears have long handles and short blades and tailors' shears just the opposite?

6. By reference to moments explain (a) why a door can be closed more easily by pushing at the knob than at a point close to the hinges; (b) why a heavier load can be lifted on a wheelbarrow having long handles than on one with short handles; (c) why a long-handled shovel generally has a smaller blade than one with a shorter handle.

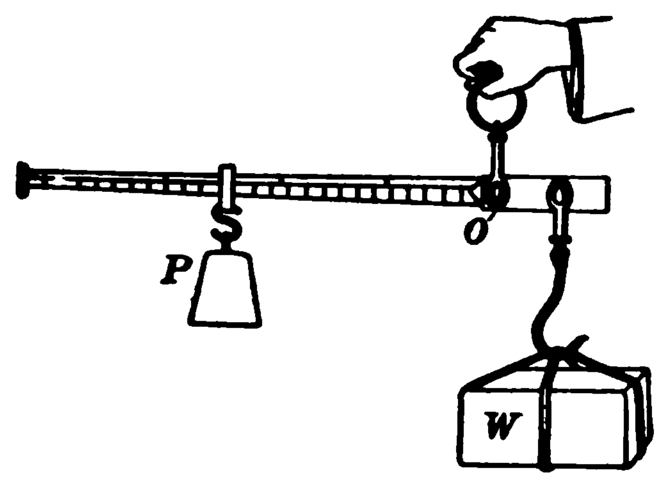


FIG. 126. Steelyards

7. Two boys carry a load of 60 lb. on a pole between them. If the load is 4 ft. from one boy and 6 ft. from the other, how many pounds does each boy carry? (Consider the force exerted by one of the boys as the effort, the load as the resistance, and the second boy as the fulcrum.)

8. Where must a load of 100 lb. be placed on a stick 10 ft. long if the man who holds one end is to support 30 lb. while the man at the other end supports 70 lb.?

9. One end of a piano must be raised to remove a broken caster. The force required is 240 lb. Make a diagram to show how a 6-foot steel bar may be used as a second-class lever to raise the piano with an effort of 40 lb.

10. When a load is carried on a stick over the shoulder, why does the pressure on the shoulder become greater as the load is moved farther out on the stick?

11. A safety valve and weight are arranged as in Fig. 127. If *ab* is $1\frac{1}{2}$ in. and *bc* $10\frac{1}{2}$ in., what effective steam pressure per square inch is required on the valve to unseat it, if the area of the valve is $\frac{1}{2}$ sq. in. and the weight of the ball 4 lb.?

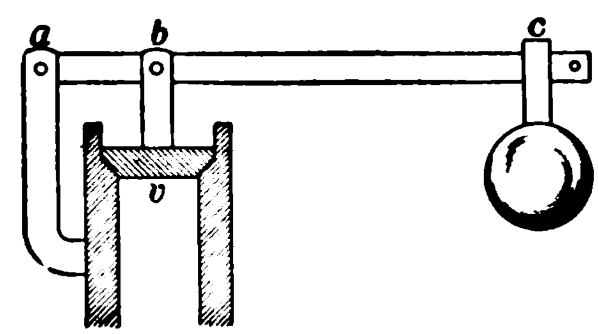


FIG. 127

12. The diameters of the piston and cylinder of a hydraulic press are respectively 3 in. and 30 in. The piston rod is attached 2 ft. from the fulcrum of a lever 12 ft. long (Fig. 12, p. 17). What force must be applied at the end of the lever to make the press exert a force of 5000 lb.?

13. Three boys sit on a seesaw as follows: A (= 75 lb.), 4 ft. to the right of the fulcrum; B (= 100 lb.), 7 ft. to the right of the fulcrum; C (= x lb.), 7 ft. to the left of the fulcrum. Equilibrium is produced by a man, 12 ft. to the right of the fulcrum, pushing up with a force of 25 lb. Find C's weight.

THE PRINCIPLE OF WORK

135. Statement of the principle of work. The study of pulleys led us to the conclusion that in all cases where such machines are used the work done by the effort is equal to the work done against the resistance, provided always that friction may be neglected and that the motions are uniform so that none of the force exerted is used in overcoming inertia. The study of levers led to precisely the same result. In Chapter II the study of the hydraulic press showed that the same law applied in this case also, for it was shown that the force on the small piston times the distance through which it moved was equal to the force on the large piston times the distance through which it moved. Similar experiments upon all sorts of machines have shown that the following is an absolutely general law: *In all mechanical devices of whatever sort, in all cases where friction may be neglected, the work expended upon the machine is equal to the work accomplished by it.*

This important generalization, called "the principle of work," was first stated by Newton in 1687. It has proved to be one of the most fruitful principles ever put forward in the history of physics. By its application it is easy to deduce the relation between the force applied and the force overcome in any sort of machine, provided only that friction is negligible and that the motions take place slowly. It is only necessary to produce, or imagine, a displacement at one end of the machine, and then to measure or calculate the corresponding displacement at the other end. The ratio of the second displacement to the first is the ratio of the force acting to the force overcome.

136. The wheel and axle. Let us apply the work principle to discover the law of the wheel and axle (Fig. 128). When the large wheel has made one revolution, the point A on the rope

moves down a distance equal to the circumference of the wheel. During this time the weight R is lifted a distance equal to the circumference of the axle. Hence the equation $Es = Rs'$ becomes $E \times 2\pi R_w = R \times 2\pi r_a$, where R_w and r_a are the radii of the wheel and axle respectively. This equation may be written in the form

$$R/E = R_w/r_a; \qquad (5)$$

that is, *the weight lifted on the axle is as many times the force applied to the wheel as the radius of the wheel is times the radius of the axle.*

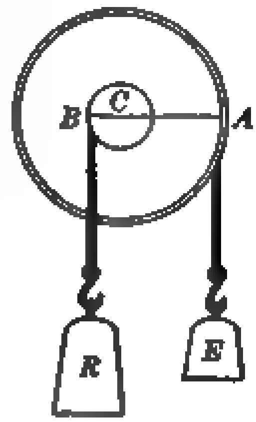


FIG. 128. The wheel and axle

Otherwise stated, *the mechanical advantage of the wheel and axle is equal to the radius of the wheel divided by the radius of the axle.*

FIG. 129. The capstan

The *capstan* (Fig. 129) is a special case of the wheel and axle, the length of the lever arm taking the place of the radius of the wheel, and the radius of the barrel corresponding to the radius of the axle.

137. The work principle applied to the inclined plane. The work done against gravity in lifting a weight R (Fig. 130) from the bottom to the top of a plane is evidently equal to R times the height h of the plane. But the work done by the acting force E while the carriage of weight R is being pulled from the bottom to the top of the plane is equal to E times the length l of the plane. Hence the principle of work gives

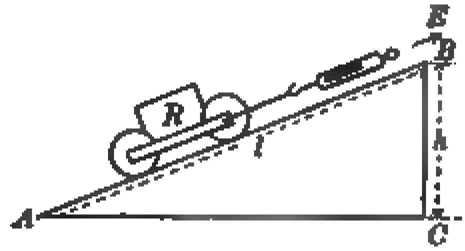


FIG. 130. The inclined plane

$$El = Rh, \text{ or } R/E = l/h; \qquad (6)$$

that is, *the mechanical advantage of the inclined plane, or the ratio of the weight lifted to the force acting parallel to the plane, is the ratio of the length of the plane to the height of the plane.* This is precisely the conclusion at which we arrived in another way in Chapter V, p. 63.

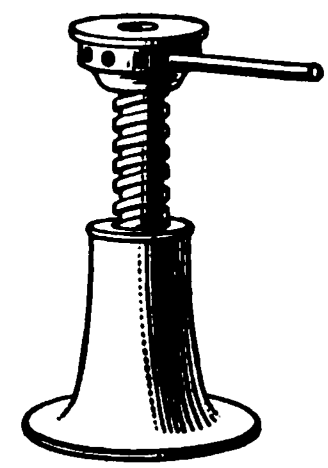


FIG. 131. The jackscrew

138. The screw. The screw (Fig. 131) is a combination of the inclined plane and the lever. Its law is easily obtained from the principle of work. When the force which acts on the end of the lever has moved this point through one complete revolution, the weight R, which rests on top of the screw, has evidently been lifted through a vertical distance equal to the distance between two adjoining threads. This distance d is called the *pitch* of the screw. Hence, if we represent by l the length of the lever, the work principle gives

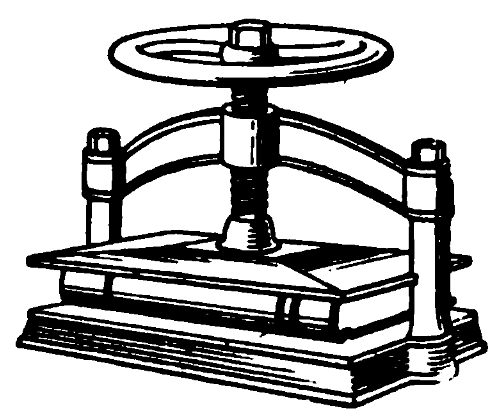


FIG. 132. The letter press

$$E \times 2\pi l = Rd; \qquad (7)$$

that is, *the mechanical advantage of the screw, or the ratio of the weight lifted to the force applied, is equal to the ratio of the circumference of the circle moved over by the end of the lever to the distance between the threads of the screw.* In actual practice the friction in such an arrangement is always very great, so that the effort exerted must always be considerably greater than that given by equation 7. The common jackscrew just described (and used chiefly for raising buildings), the letter press (Fig. 132), and the vise (Fig. 133) are all familiar forms of the screw.

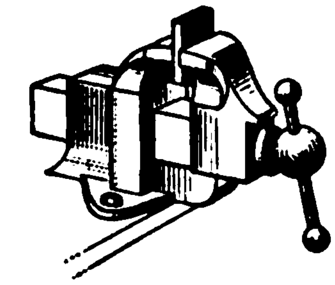


FIG. 133. The vise

139. A train of gear wheels. A form of machine capable of very high mechanical advantage is the train of gear wheels shown in Fig. 134.

Let the student show from the principle of work, namely $Es = Rs'$, that the mechanical advantage, that is, $\frac{R}{E}$, of such a device is

$$\frac{\text{circum. of } a}{\text{circum. of } e} \times \frac{\text{no. cogs in } d}{\text{no. cogs in } c} \times \frac{\text{no. cogs in } f}{\text{no. cogs in } b}. \quad (8)$$

140. The worm wheel. Another device of high mechanical advantage is the worm wheel (Fig. 135). Show that if l is the length of the crank arm C, n the number of teeth in the cogwheel W, and r the radius of the axle, the mechanical advantage is given by

$$\frac{2\pi ln}{2\pi r} = n\frac{l}{r}. \quad (9)$$

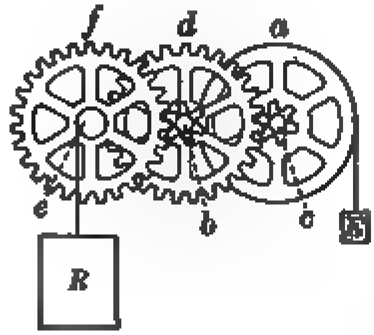


Fig. 134. Train of gear wheels

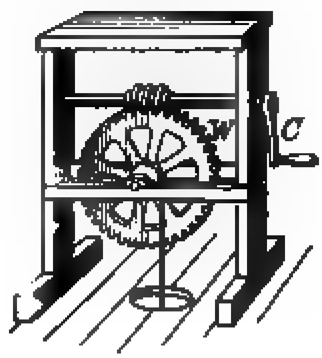


Fig. 135. The worm gear

This device is used most frequently when the primary object is to decrease speed rather than to multiply force. It will be seen that the crank handle must make n turns while the cogwheel is making one. The worm-gear "drive" is generally used in the rear axles of auto trucks.

141. The differential pulley. In the differential pulley (Fig. 136) an endless chain passes first over the fixed pulley A, then down and around the movable pulley C, then up again over the fixed pulley B, which is rigidly attached to A, but differs slightly from it in diameter. On the circumference of all the pulleys are projections which fit between the links, and thus keep the chains from slipping. When the chain is pulled down at E, as in Fig. 136, (2), until the upper rigid system of pulleys has made one complete revolution, the chain between the upper and lower pulleys has been shortened by the difference between the circumferences of the

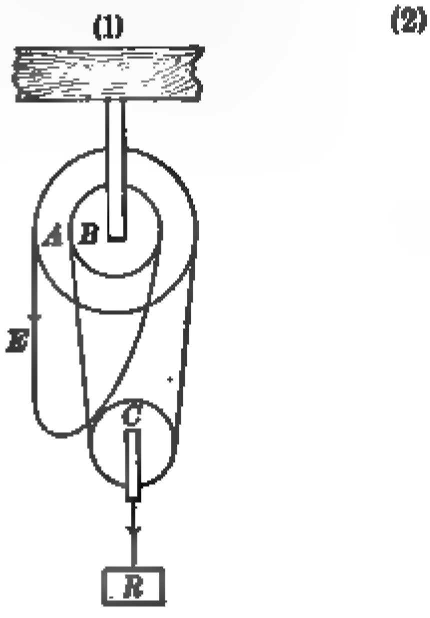


Fig. 136. The differential pulley

pulleys A and B, for the chain has been pulled up a distance equal to the circumference of the larger pulley and let down a distance equal to the circumference of the smaller pulley. Hence the load R has been lifted by half the difference between the circumferences of A and B. The mechanical advantage is therefore equal to the circumference of A divided by one half the difference between the circumferences of A and B.

QUESTIONS AND PROBLEMS

1. A 1500-pound safe must be raised 5 ft. The force which can be applied is 250 lb. What is the shortest inclined plane which can be used for the purpose?

2. A 300-pound barrel was rolled up a plank 12 ft. long into a doorway 3 ft. high. What force was applied parallel to the plank?

3. A force of 80 kg. on a wheel whose diameter is 3 m. balances a weight of 150 kg. on the axle. Find the diameter of the axle.

4. If the capstan of a ship is 12 in. in diameter and the levers are 6 ft. long, what force must be exerted by each of 4 men in order to raise an anchor weighing 2000 lb.?

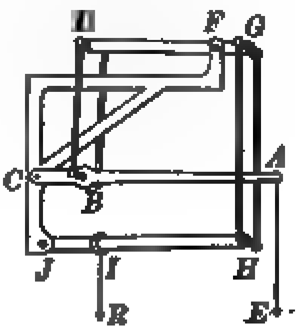


Fig. 137. The compound lever

5. If, in the compound lever of Fig. 137, $AC = 6$ ft., $BC = 1$ ft., $DF = 4$ ft., $FG = 8$ in., $HJ = 5$ ft., and $IJ = 2$ ft., what force applied at E will support a weight of 2000 lb. at R?

Fig. 138. Hay scales

Fig. 139. Windlass with gears

6. The hay scales shown in Fig. 138 consist of a compound lever with fulcrums at F, F', F'', F'''. If Fo and $F'o'$ are lengths of 6 in., FE and $F'E$ 5 ft., $F''n$ 1 ft., $F''m$ 6 ft., rF''' 2 in., and $F'''S$ 20 in., how many pounds at W will be required to balance a weight of a ton on the platform?

7. In the windlass of Fig. 139 the crank handle has a length of 2 ft., and the barrel a diameter of 8 in. There are 20 cogs in the small cogwheel and 60 in the large one. What is the mechanical advantage of the arrangement?

8. If in the crane of Fig. 140 the crank arm has a length of $\frac{1}{2}$ m., and the gear wheels A, B, C, and D have respectively 12, 48, 12, and 60 cogs, while the axle over which the chain runs has a radius of 10 cm., what is the mechanical advantage of the crane?

9. If a worm wheel (Fig. 135) has 30 teeth, and the crank is 25 cm. long, while the radius of the axle is 3 cm., what is the mechanical advantage of the arrangement?

10. A small jackscrew has 20 threads to the inch. Using a lever $3\frac{1}{4}$ in. long will give what mechanical advantage? (Use 3.1416.)

Fig. 140. The crane

11. The screw of a letter press has 5 threads to the inch, and the diameter of the wheel is 12 in. If there were no friction, what pressure would result from a rotating force of 20 lb. applied to the wheel?

12. Eight jackscrews, each of which has a pitch of $\frac{1}{4}$ in. and a lever arm of 18 in., are being worked simultaneously to raise a building weighing 100,000 lb. What force would have to be exerted at the end of each lever if there were no friction? What if 75% were wasted in friction?

13. What is gained by using a machine whose mechanical advantage is $\frac{1}{4}$? Name two or three household appliances whose mechanical advantage is less than 1.

Power and Energy

142. Definition of power. When a given load has been raised a given distance a given amount of work has been done, whether the time consumed in doing it is small or great. Time is therefore not a factor which enters into the determination of work; but it is often as important to know the *rate* at which work is done as to know the *amount* of work

accomplished. *The rate of doing work is called power, or activity.* Thus, if P represent power, W the work done, and t the time required to do it,

$$P = \frac{W}{t}. \tag{10}$$

143. Horse power. James Watt (1736–1819), the inventor of the steam engine, considered that an average horse could do 33,000 foot pounds of work per minute, or 550 foot pounds per second. The metric equivalent is 76.05 kilogram meters per second. This number is probably considerably too high, but it has been taken ever since, in English-speaking countries, as the unit of power, and named the *horse power* (H.P.). The power of steam engines has usually been rated in horse power. The horse power of an ordinary railroad locomotive is from 500 to 1000. Stationary engines and steamboat engines of the largest size often run from 5000 to 20,000 H.P. The power of an average horse is about $\frac{3}{4}$ H.P., and that of an ordinary man about $\frac{1}{7}$ H.P.

144. The kilowatt. In the metric system the erg has been taken as the absolute unit of work. The corresponding unit of power is an erg per second. This is, however, so small that it is customary to take as the practical unit 10,000,000 ergs per second; that is, one joule per second (see § 125, p. 106). This unit is called the *watt*, in honor of James Watt. The power of dynamos and electric motors is almost always expressed in kilowatts, a kilowatt representing 1000 watts; and in modern practice even steam engines are being increasingly rated in kilowatts rather than in horse power. A horse power is equivalent to 746 watts, or about $\frac{3}{4}$ of a kilowatt. A kilowatt is almost exactly equal to 102 kilogram meters per second.

145. Definition of energy. The *energy* of a body is defined as its *capacity for doing work.* In general, inanimate bodies possess energy only because of work which has been done upon them at some previous time. Thus, suppose a kilogram weight

JAMES PRESCOTT JOULE
(1818–1889)

English physicist, born at Manchester; most prominent figure in the establishment of the doctrine of the conservation of energy; studied chemistry as a boy under John Dalton, and became so interested that his father, a prosperous Manchester brewer, fitted out a laboratory for him at home; conducted most of his researches either in a basement of his own house or in a yard adjoining his brewery; discovered the law of heating a conductor by an electric current; carried out, in connection with Lord Kelvin, epoch-making researches upon the thermal properties of gases; did important work in magnetism; first proved experimentally the identity of various forms of energy

JAMES WATT (1736–1819)

The Scotch instrument maker at the University of Glasgow, who may properly be considered the inventor of the steam engine, for, although a crude and inefficient type of steam engine was known before his time, he left it in essentially its present form. The modern industrial era may be said to begin with Watt

The *Rocket* and the *Virginian Mallet*

This picture shows the relative sizes of Stephenson's original locomotive, the *Rocket*, which ran in October, 1829, between Manchester and Liverpool, and the largest locomotive thus far built, the *Virginian Mallet*, constructed in the shops of the American Locomotive Company at Schenectady, New York, for use on the Virginian Railroad. The *Rocket* weighed 4½ tons and won a £500 prize by drawing a coach containing thirty people at a rate of from 26 to 30 miles per hour. The *Virginian Mallet* weighs 450 tons and has a tractive power of 176,600 pounds. Its horse power is approximately 5100

is lifted from the first position in Fig. 141 through a height of 1 m. and placed upon the hook H at the end of a cord which passes over a frictionless pulley p and is attached at the other end to a second kilogram weight B. The operation of lifting A from position *1* to position *2* has required an expenditure upon it of 1 kg. m. (100,000 g. cm., or 98,000,000 ergs) of work. But in position *2*, A is itself possessed of a certain capacity for doing work which it did not have before; for if it is now started downward by the application of the slightest conceivable force, it will, of its own accord, return to position *1*, and will in so doing raise the kilogram weight B through a height of 1 m. In other words, it will do upon B exactly the same amount of work that was originally done upon it.

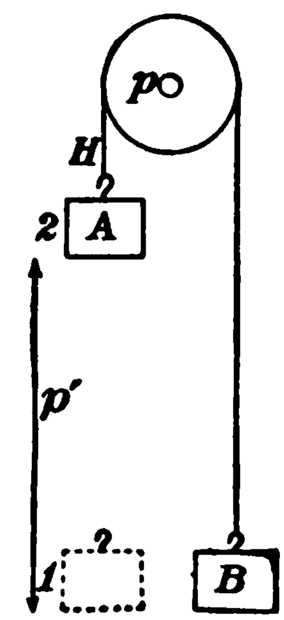


Fig. 141. Illustration of potential energy

146. Potential and kinetic energy. A body may have a capacity for doing work not only because it has been given an elevated position but also because it has in some way acquired velocity; for example, a heavy flywheel will keep machinery running for some time after the power has been shut off, and a bullet shot upward will lift itself a great distance against gravity because of the velocity which has been imparted to it. Similarly, any body which is in motion is able to rise against gravity, or to set other bodies in motion by colliding with them, or to overcome resistances of any conceivable sort. Hence, in order to distinguish between the energy which a body may have because of an *advantageous position*, and the energy which it may have because it is in *motion*, the two terms "potential energy" and "kinetic energy" are used. Potential energy includes the energy of lifted weights, of coiled or stretched springs, of bent bows, etc.,—in a word, *potential energy is energy of position, while kinetic energy is energy of motion.*

147. Transformations of potential and kinetic energy. The swinging of a pendulum and the oscillation of a weight attached to a spring illustrate well the way in which energy which has once been put into a body may be transformed back and forth between the potential and kinetic varieties. When the pendulum bob is at rest at the bottom of its arc, it possesses no energy of either type, since, on the one hand, it is as low as it can be, and, on the other, it has no velocity. When we pull it up the arc to the position *A* (Fig. 142), we do an amount of work upon it which is equal in gram centimeters to its weight in grams times the distance *AD* in centimeters; that is, we store up in it this amount of potential energy. As now the bob falls to *C* this potential energy is completely transformed into kinetic energy. That this kinetic energy at *C* is exactly equal to the potential energy at *A* is proved by the fact that if friction is completely eliminated, the bob rises to a point *B* such that *BE* is equal to *AD*. We see, therefore, that at the ends of its swing the energy of the pendulum is all potential, while in the middle of the swing its energy is all kinetic. In intermediate positions the energy is part potential and part kinetic, but the sum of the two is equal to the original potential energy.

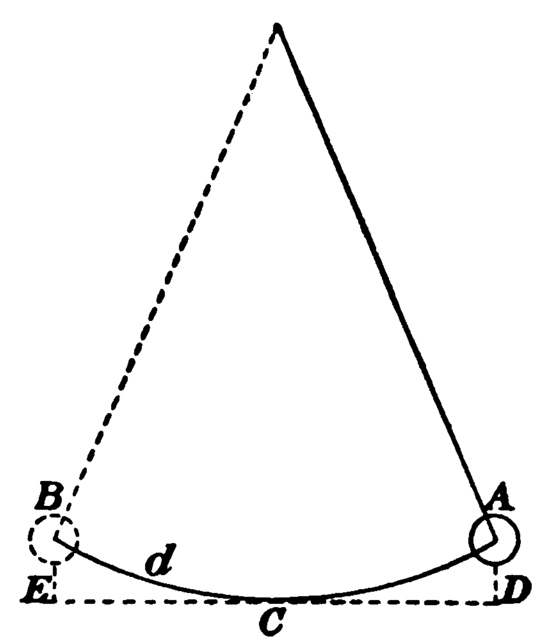


FIG. 142. Transformation of potential and kinetic energy

148. General statement of the law of frictionless machines. In our development of the law of machines, which led us to the conclusion that the work of the acting force is always equal to the work of the resisting force, we were careful to make two important assumptions: first, that friction was negligible; second, that the motions were all either uniform or so slow that no appreciable velocities were imparted. In other words,

we assumed that the work of the acting force was expended simply in lifting weights or compressing springs, — that is, in storing up potential energy. If now we drop the second assumption, a very simple experiment will show that our conclusion must be somewhat modified. Suppose, for instance, that instead of lifting a 500-gram weight slowly by means of a balance, we jerk it up suddenly. We shall now find that the initial pull indicated by the balance, instead of being 500 g., will be considerably more, — perhaps as much as several thousand grams if the pull is sufficiently sudden. This is obviously because the acting force is now overcoming not merely the 500 g. which represents the resistance of gravity, but also the inertia of the body, since velocity is being imparted to it. Now work done in imparting velocity to a body, that is, in overcoming its inertia, always appears as *kinetic* energy, while work done in overcoming gravity appears as the *potential* energy of a lifted weight. Hence, whether the motions produced by machines are slow or fast, if friction is negligible the law for all devices for transforming work may be stated thus: *The work of the acting force is equal to the sum of the potential and kinetic energies stored up in the mass acted upon.* In machines which work against gravity the body usually starts from rest and is left at rest, so that the kinetic energy resulting from the whole operation is zero. Hence in such cases the work done is the weight lifted times the height through which it is lifted, whether the motion is slow or fast. The kinetic energy imparted to the body in starting is all given up by it in stopping.

149. The measure of potential energy. The measure of the potential energy of any lifted body, such as a lifted pile driver, is equal to the work which has been spent in lifting the body. Thus, if h is the height in centimeters and M the weight in grams, then the potential energy P.E. of the lifted mass is

$$\text{P.E.} = Mh \text{ gram centimeters.} \qquad (11)$$

Similarly, if h is the height in feet, and M the mass in pounds,

$$\text{P.E.} = Mh \text{ foot pounds.}$$

150. The measure of kinetic energy. Since the force of the earth's attraction for M grams is Mg dynes, if we wish to express the potential energy in ergs instead of in gram centimeters, we have

$$\text{P.E.} = Mgh \text{ ergs.} \tag{12}$$

Since this energy is all transformed into kinetic energy when the mass falls the distance h, the product Mgh also represents the number of ergs of kinetic energy which the moving weight has when it strikes the pile.

If we wish to express this kinetic energy in terms of the velocity with which the weight strikes the pile, instead of the height from which it has fallen, we have only to substitute for h its value in terms of g and the velocity acquired (see equation (3), p. 76), namely $h = v^2/2\,g$. This gives the kinetic energy K.E. in the form

$$\text{K.E.} = \tfrac{1}{2}\,Mv^2 \text{ ergs.} \tag{13}$$

Since it makes no difference how a body has acquired its velocity, this represents the general formula for the kinetic energy *in ergs* of any moving body, in terms of its mass and its velocity.

Thus, the kinetic energy of a 100-gram bullet moving with a velocity of 10,000 cm. per second is

$$\text{K.E.} = \tfrac{1}{2} \times 100 \times (10{,}000)^2 = 5{,}000{,}000{,}000 \text{ ergs.}$$

Since 1 g. cm. is equivalent to 980 ergs, the energy of this bullet is $\frac{5{,}000{,}000{,}000}{980} = 5{,}102{,}000$ g. cm., or 51.02 kg. m.

We know, therefore, that the powder pushing on the bullet as it moved through the rifle barrel did 51.02 kg. m. of work upon the bullet in giving it the velocity of 100 m. per second.

In general terms, if M is in grams and v in centimeters per second, $\text{K.E.} = \dfrac{Mv^2}{2 \times 980}$ g. cm.; if M is in pounds and v in feet per second, $\text{K.E.} = \dfrac{Mv^2}{2 \times 32.16}$ ft. lb.

QUESTIONS AND PROBLEMS

1. A stick of dynamite has great capacity for doing work. Before the explosion occurs, is the energy in the potential or the kinetic form?

2. Explain the use of the sand blast in cleaning castings, making frosted glass, cutting figures on glassware, cleaning off the walls of stone buildings, etc.

3. How much work is required to lift the 500-pound weight of a pile driver 30 ft.? How much potential energy is then stored in it? How much work does it do when it falls? If the falling mass drives the pile into the earth $\frac{1}{2}$ ft., what is its average force upon the pile?

4. A man weighing 198 lb. walked to the top of the stairway of the Washington Monument (500 ft. high) in 10 min. At what horse-power rate did he work?

5. A farm tractor drew a gang plow at the rate of $2\frac{1}{2}$ mi. per hour, maintaining an average drawbar pull of 1500 lb. At what average H.P. was the tractor working?

6. In the course of a stream there is a waterfall 22 ft. high. It is shown by measurement that 450 cu. ft. of water per second pours over it. How many foot pounds of energy per second could be obtained from it? What horse power?

7. How many gallons of water (8 lb. each) could a 10-horse-power engine raise in one hour to a height of 60 ft.?

8. A certain airplane using three 400-horse-power motors flew 80 mi. per hour. With how many pounds backward force did the propellers push against the air?

9. If a rifle bullet can just pass through a plank, how many planks will it pass through if its speed is doubled?

10. A steel ball dropped into a pail of moist clay from a height of a meter sinks to a depth of 2 cm. How far will it sink if dropped 4 m.?

11. Neglecting friction, find how much force a boy would have to exert to pull a 100-pound wagon up an incline which rises 5 ft. for every 100 ft. of length traversed on the incline. In addition to giving the numerical solution of the problem, state why you solve it as you do and how you know that your solution is correct.

CHAPTER VIII

THERMOMETRY; EXPANSION COEFFICIENTS*

THERMOMETRY

151. Meaning of temperature. When a body feels hot to the touch we are accustomed to say that it has a *high temperature*, and when it feels cold that it has a *low temperature.* Thus the word "temperature" is used to denote the condition of hotness or coldness of the body whose state is being described.

152. Measurement of temperature. So far as we know, up to the time of Galileo no one had ever used any special instrument for the measurement of temperature. People knew how hot or how cold it was from their feelings only. But under some conditions this temperature sense is a very unreliable guide. For example, if the hand has been in hot water, tepid water will feel cold; while if it has been in cold water, the same tepid water will feel warm; a room may feel hot to one who has been running, while it will feel cool to one who has been sitting still.

Difficulties of this sort have led to the introduction in modern times of mechanical devices, called *thermometers*, for measuring temperature. These instruments depend for their operation upon the fact that almost all bodies expand as they grow hot.

153. Galileo's thermometer. It was in 1592 that Galileo, at the University of Padua in Italy, constructed the first

* It is recommended that this chapter be preceded by laboratory measurements on the expansions of a gas and a solid. See, for example, Experiments 14 and 15 of the authors' Manual.

thermometer. He was familiar with the facts of expansion of solids, liquids, and gases; and since gases expand more than solids or liquids, he chose a gas as his expanding substance. His device was that shown in Fig. 143.

Let a bulb of air *B* be connected with a water manometer *m*, as in Fig. 143. If the bulb is warmed by holding a Bunsen burner beneath it, or even by placing the hand upon it, the water at *m* will at once begin to descend, showing that the pressure exerted by the air contained in the bulb has been increased by the increase in its temperature. If *B* is cooled with ice or ether, the water will rise at *m*.

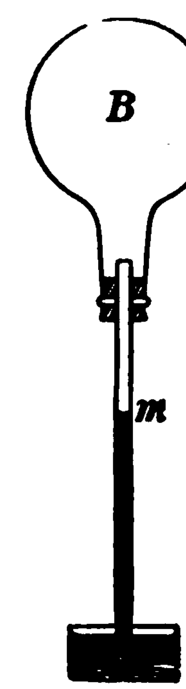


FIG. 143. **Expansion of air by heat**

154. Significance of temperature from the standpoint of the kinetic theory. Now if, as was stated in § 64, gas pressure is due to the bombardment of the walls by the molecules of the gas, since the number of molecules in the bulb can scarcely have been changed by slightly heating it we are forced to conclude that the increase in pressure is due to an increase in the *velocity* of the molecules which are already there. From the standpoint of the kinetic theory the pressure exerted by a given number of molecules of a gas is determined by the kinetic energy of bombardment of these molecules against the containing walls. To increase the temperature is to increase the average kinetic energy of the molecules, and to diminish the temperature is to diminish this average kinetic energy. The kinetic theory thus furnishes a very simple and natural explanation of the fact of the expansion of gases with a rise in temperature.

155. The construction of a centigrade mercury thermometer. It was not until about 1700 that mercury thermometers were invented. On account of their extreme convenience these have now replaced all others for practical purposes.

The meaning of a degree of temperature change as measured by a mercury thermometer is best understood from a description of the method of making and graduating the thermometer.

A bulb is blown at one end of a piece of thick-walled glass tubing of small, uniform bore. Bulb and tube are filled with mercury, at a temperature slightly above the highest temperature for which the thermometer is to be used, and the tube is sealed off in a hot flame. As the mercury cools, it contracts and falls away from the top of the tube, leaving a vacuum above it.

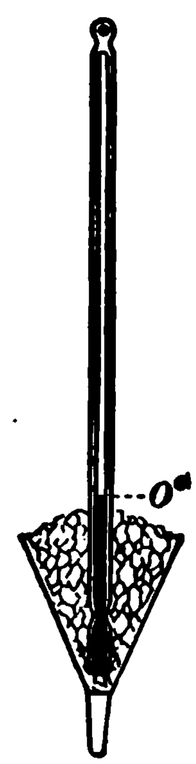


FIG. 144. Method of finding the 0° point in calibrating a thermometer

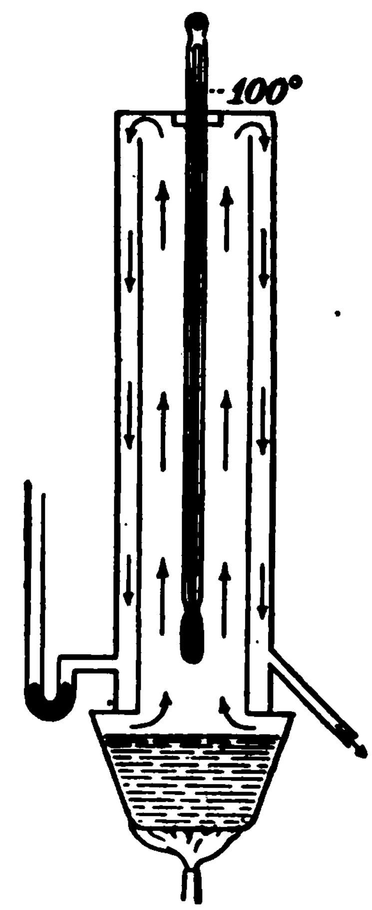


FIG. 145. Method of finding the 100° point in calibrating a thermometer

The bulb is next surrounded with melting snow or ice, as in Fig. 144, and the point at which the mercury stands in the tube is marked 0°. Then the bulb and tube are placed in the steam rising from boiling water under a pressure of 76 cm., as in Fig. 145, and the new position of the mercury is marked 100°. The space between these two marks on the stem is then divided into 100 equal parts, and divisions of the same length are extended above the 100° mark and below the 0° mark.

One degree of change in temperature, measured on such a thermometer, means, then, such a temperature change as will cause the mercury in the stem to move over one of these divisions; that is, it is such a temperature change as will cause mercury contained in a glass bulb to expand $\frac{1}{100}$ of the amount which it expands in passing from the temperature

of melting ice to that of steam under a pressure of 76 cm. A thermometer in which the scale is divided in this way is called a centigrade thermometer.

Thermometers graduated on the centigrade scale are used almost exclusively in scientific work, and also for ordinary purposes in most countries which have adopted the metric system. This scale was first devised in 1742 by Celsius, of Upsala, Sweden. For this reason it is sometimes called the Celsius instead of the centigrade scale.

According to the kinetic theory an increase in temperature in a liquid, as in a gas, means an increase in the mean kinetic energy of the molecules; and, conversely, a decrease in temperature means a decrease in this average kinetic energy.

156. Fahrenheit thermometers. The common household thermometer in England and the United States differs from the centigrade only in the manner of its graduation. In its construction the temperature of melting ice is marked 32° instead of 0°, and that of boiling water 212° instead of 100°. The intervening stem is then divided into 180 parts. The zero of this scale is the temperature obtained by mixing equal weights of sal ammoniac (ammonium chloride) and snow. In 1714, when Fahrenheit devised this scale, he chose this zero because he thought it represented the lowest possible temperature that could be obtained in the laboratory.

Fig. 146. The centigrade and Fahrenheit scales

157. Comparison of centigrade and Fahrenheit thermometers. From the methods of graduation of the Fahrenheit and centigrade thermometers it will be seen that 100° on the centigrade scale denotes the same difference of temperature as 180° on the Fahrenheit scale (Fig. 146). Hence five

centigrade degrees are equal to nine Fahrenheit degrees. In Fig. 147, C represents the number of degrees in the centigrade reading, while F represents the number in the Fahrenheit reading. Since five centigrade degrees cover the same space on the stem as nine of the smaller Fahrenheit degrees, it is evident that

$$\frac{C}{F-32}=\frac{5}{9}.$$

By this expression of the relation of the two scales it is very easy to reduce the readings of one thermometer to the scale of the other.

For example, to find what Fahrenheit reading corresponds to 20° C. we have

$$\frac{20}{F-32}=\frac{5}{9},\quad F=68°.$$

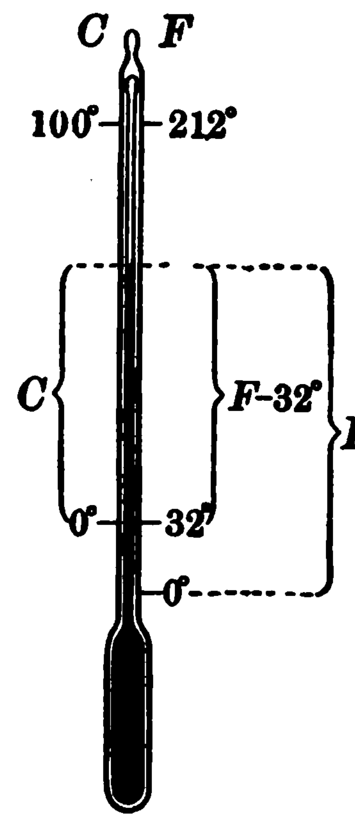


FIG. 147. Comparison of centigrade and Fahrenheit scales

158. The range of the mercury thermometer. Since mercury freezes at – 39° C., temperatures lower than this are very often measured by means of *alcohol* thermometers, for the freezing point of alcohol is – 130° C. Similarly, since the boiling point of mercury is about 360° C., mercury thermometers cannot be used for measuring very high temperatures. For both very high and very low temperatures — in fact, for all temperatures — a *gas* thermometer is the standard instrument.

159. The standard hydrogen thermometer. The modern gas thermometer (Fig. 148) is, however, widely different from that devised by Galileo (Fig. 143). It is not usually the increase in the volume of a gas kept under constant pressure which is taken as the measure of temperature change, but rather the increase in pressure which the molecules of a confined gas exert against the walls of a vessel whose volume is kept constant. The essential features of the method of calibration and use

of the standard hydrogen thermometer at the International Bureau of Weights and Measures at Paris are as follows:

The bulb B (Fig. 148) is first filled with hydrogen and the space above the mercury in the tube a made as nearly a perfect vacuum as possible. B is then surrounded with melting ice (as in Fig. 144) and the tube a raised or lowered until the mercury in the arm b stands exactly opposite the fixed mark c on the tube. Now, since the space above D is a vacuum, the pressure exerted by the hydrogen in B against the mercury surface at c just supports the mercury column ED. The point D is marked on a strip of metal behind the tube a. The bulb B is then placed in a steam bath like that shown in Fig. 145. The increased pressure of the gas in B at once begins to force the mercury down at c and up at D. But by raising the arm a the mercury in b is forced back again to c, the increased pressure of the gas on the surface of the mercury at c being balanced by the increased height of the mercury column supported, which is now EF instead of ED. When the gas in B is thoroughly heated to the temperature of the steam, the arm a is very carefully adjusted so that the mercury in b stands very exactly at c, its original level. A second mark is then placed on the metal strip exactly opposite the new level of the mercury, that is, at F. Then D is marked 0° C., and F is marked 100° C. The vertical distance between these marks is divided into 100 exactly equal parts. Divisions of exactly the same length are carried above the 100° mark and below the 0° mark. One degree of change in temperature is then defined as any change in temperature which will cause the pressure of the gas in B to change by the amount represented by the distance between any two of these divisions. This distance is found to be $\frac{1}{273}$ of the height ED.

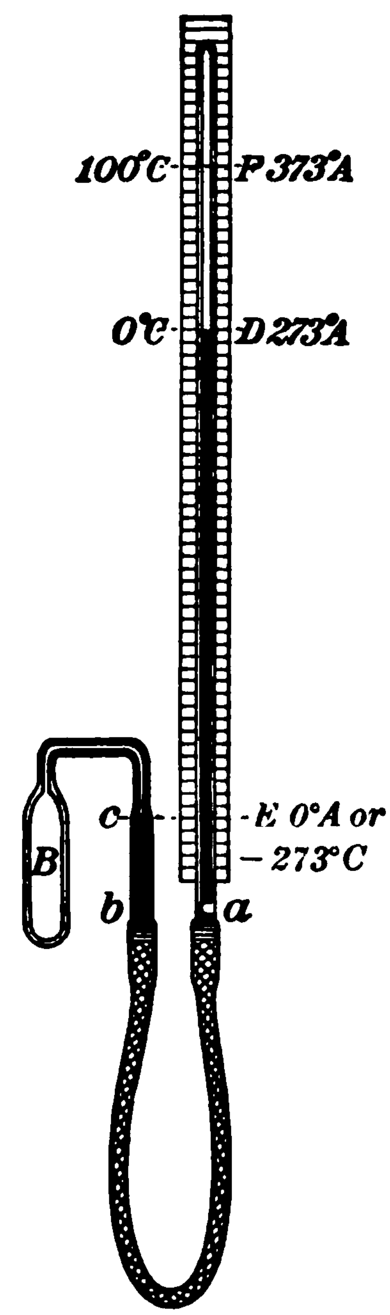


FIG. 148. The standard gas thermometer

In other words, *one degree of change in temperature on the centigrade scale is such a temperature change as will cause the*

pressure exerted by a confined volume of hydrogen to change by $\frac{1}{273}$ *of its pressure at the temperature of melting ice* (0° C.).

160. Absolute temperature. Since, then, cooling the hydrogen through 1° C., as defined above, reduces the pressure $\frac{1}{273}$ of its value at 0° C., it is clear that cooling it 273° below 0° C. would reduce its pressure to zero. But from the standpoint of the kinetic theory this would be the temperature at which all motions of the hydrogen molecules would cease. This temperature is called the *absolute zero*, and the temperature measured from this zero is called *absolute temperature.* Thus, if A is used to denote the absolute scale, we have 0° C. = 273° A., 100° C. = 373° A., 15° C. = 288° A., etc. It is customary to indicate temperatures on the centigrade scale by t, and on the absolute scale by T. We have, then,

$$T = t + 273. \qquad (1)$$

161. Comparison of gas and mercury thermometers. Since an international committee has chosen the hydrogen thermometer described in § 159 as the standard of temperature measurement, it is important to know whether mercury thermometers, graduated in the manner described in § 155, agree with gas thermometers at temperatures other than 0° and 100° (where, of course, they must agree, since these temperatures are in each case the starting points of the graduation). A careful comparison has shown that although they do not agree exactly, yet fortunately the disagreements at ordinary temperatures are small, not amounting to more than .2° anywhere between 0° and 100°. At 300° C., however, the difference amounts to about 4°. (Mercury thermometers are actually used for measuring temperatures above the boiling point of mercury, 360°C. They are then filled with nitrogen, the pressure of which prevents boiling.)

Hence for all ordinary purposes mercury thermometers are sufficiently accurate, and no special standardization of them is necessary. But in all scientific work, if mercury thermometers are used at all, they must first be compared with a gas thermometer and a table of corrections obtained. The errors of an alcohol thermometer are considerably larger than those of a mercury thermometer.

162. Low temperatures. The absolute zero of temperature can, of course, never be attained, but in recent years rapid

Sir William Thomson, Lord Kelvin (1824–1907)

One of the best known and most prolific of nineteenth-century physicists; born in Belfast, Ireland; professor of physics in Glasgow University, Scotland, for more than fifty years; especially renowned for his investigations in heat and electricity; originator of the absolute thermodynamic scale of temperature; formulator of the second law of thermodynamics; inventor of the electrometer, the mirror galvanometer, and many other important electrical devices

THE *CLERMONT* AND THE *LEVIATHAN*

This page shows the relative sizes of Robert Fulton's *Clermont*, the first successful steamboat, and the *Leviathan*, the largest ship in the world. The *Clermont* was 150 ft. long and 13 ft. wide, and had a displacement of about 100 tons. In August, 1807, she ran from New York to Albany and back at an average speed of 5 mi. per hour. The *Leviathan*, used by the United States government during the World War for the transportation of troops, carried more than 10,000 soldiers per trip in addition to her officers and crew. She is 950 ft. long and 100 ft. wide and has a maximum displacement of 58,000 tons. She has four turbine engines, aggregating 90,000 horse power, to drive four propellers. On her trial trip she developed a speed of 25.8 knots per hour

strides have been made toward it. Forty years ago the lowest temperature which had ever been measured was $-110°$ C., the temperature attained by Faraday in 1845 by causing a mixture of ether and solid carbon dioxide to evaporate in a vacuum. But in 1880 air was first liquefied and found, by means of a gas thermometer, to have a temperature of $-190°$ C. When liquid air evaporates into a space which is kept exhausted by means of an air pump, its temperature falls to about $-220°$ C. Recently hydrogen has been liquefied and found to have a temperature at atmospheric pressure of $-243°$ C. All of these temperatures have been measured by means of hydrogen thermometers. By allowing liquid hydrogen to evaporate into a space kept exhausted by an air pump, Dewar in 1900 attained a temperature of $-260°$. In 1911 Kamerlingh Onnes liquefied helium and attained a temperature of $-271.3°$ C., only 1.7° above absolute zero (see § 217).

QUESTIONS AND PROBLEMS

1. Define 0° C. and 100° C. What is 1° C.? 1° F.?

2. From a study of the behavior of gases we conclude that there is a temperature at which the molecules are at rest and at which bodies therefore contain no heat. Give the reasoning that leads to this conclusion.

3. Normal room temperature is 68° F. What is it centigrade?

4. The normal temperature of the human body is 98.6° F. What is it centigrade?

5. What temperature centigrade corresponds to 0° F.?

6. Mercury freezes at about $-40°$ F. What is this centigrade?

7. The temperature of liquid air is $-190°$C. What is it Fahrenheit?

8. The lowest temperature attainable by evaporating liquid helium is $-271.3°$ C. What is it Fahrenheit?

9. What is the absolute zero of temperature on the Fahrenheit scale?

10. Why is a fever thermometer made with a very long cylindrical bulb instead of a spherical one?

11. When the bulb of a thermometer is placed in hot water, it at first falls a trifle and then rises. Why?

12. How does the distance between the 0° mark and the 100° mark vary with the size of the bore, the size of the bulb remaining the same?

13. What is meant by the absolute zero of temperature?

14. Why is the temperature of liquid air lowered if it is placed under the receiver of an air pump and the air exhausted?

15. Two thermometers have bulbs of equal size. The bore of one has a diameter twice that of the other. What are the relative lengths of the stems between 0° and 100°?

Expansion Coefficients

163. The laws of Charles and Gay-Lussac. When, as in the experiment described in § 159, we keep the volume of a gas constant and observe the rate at which the pressure increases with the rise in temperature, we obtain *the pressure coefficient of expansion*, which is defined as *the ratio between the increase in pressure per degree and the value of the pressure at* 0° *C.* This was first done for different gases by a Frenchman, Charles, in 1787, who found that *the pressure coefficients of expansion of all gases are the same.* This is known as *the law of Charles.*

When we arrange the experiment so that the gas can expand as the temperature rises, the pressure remaining constant, we obtain *the volume coefficient of expansion*, which is defined as *the ratio between the increase in volume per degree and the total volume of the gas at* 0° *C.* This was first done for different gases in 1802 by another Frenchman, Gay-Lussac, who found that *all gases have the same volume coefficient of expansion*, this coefficient being the same as the pressure coefficient, namely, 1/273. This is known as *the law of Gay-Lussac.*

From the definition of absolute temperature and from Charles's law we learn that, for all gases at constant volume, *pressure is proportional to absolute temperature*; that is,

$$\frac{P_1}{P_2}=\frac{T_1}{T_2}. \tag{2}$$

Also, from Gay-Lussac's law we learn that, for all gases at constant pressure, *volume is proportional to absolute temperature*; that is,

$$\frac{V_1}{V_2}=\frac{T_1}{T_2}. \tag{3}$$

If pressure, temperature, and volume all vary,* we have

$$\frac{P_1V_1}{P_2V_2}=\frac{T_1}{T_2}. \tag{4}$$

Any one of these six quantities may be found if the other five are known.

If the volume remains constant, that is, if $V_1 = V_2$, equation (4) reduces to (2), that is, to Charles's law. If the pressure remains constant, $P_1 = P_2$ and equation (4) reduces to (3), that is, to Gay-Lussac's law. If the temperature does not change, $T_1 = T_2$ and equation (4) reduces to $P_1V_1 = P_2V_2$, that is, to Boyle's law. If the ratio of densities instead of volumes is sought, it is only necessary to replace $\frac{V_1}{V_2}$ in (3) and (4) by $\frac{D_2}{D_1}$.

QUESTIONS AND PROBLEMS

1. Why is it unsafe to let a pneumatic inkstand like that of Fig. 30, p. 33, remain in the sun?

2. To what temperature must a cubic foot of gas initially at 0° C. be raised in order to double its volume, the pressure remaining constant?

3. If the volume of a quantity of air at 30° C. is 200 cc., at what temperature will its volume be 300 cc., the pressure remaining the same?

4. If the air within a bicycle tire is under a pressure of 2 atmospheres, that is, 152 cm. of mercury, when the temperature is 10° C., what pressure will exist within the tube when the temperature changes to 35° C.?

5. If the pressure to which 15 cc. of air is subjected changes from 76 cm. to 40 cm., the temperature remaining constant, what does its volume become? (See Boyle's law, p. 36.) If, then, the temperature of the same gas changes from 15° C. to 100° C., the pressure remaining constant, what will be the final volume?

6. The air within a half-inflated balloon occupies a volume of 100,000 l. The temperature is 15° C. and the barometric height 75 cm. What will be its volume after the balloon has risen to the height of Mt. Blanc, where the pressure is 37 cm. and the temperature − 10° C.?

* If this is not clear to the student, let him recall that if the speeds of two runners are the same, then their distances are proportional to their times, that is, $D_1/D_2 = t_1/t_2$; but if their times are the same and the speeds different, $D_1/D_2 = s_1/s_2$. If now one runs both twice as fast and twice as long, he evidently goes 4 times as far; that is, if time and speed both vary, $D_1/D_2 = t_1s_1/t_2s_2$.

Expansion of Liquids and Solids

164. The expansion of liquids. The expansion of liquids differs from that of gases in that

1. The coefficients of expansion of liquids are all considerably smaller than those of gases.

2. Different liquids expand at wholly different rates; for example, the coefficient of alcohol between 0° and 10° C. is .0011; of ether it is .0015; of petroleum, .0009; of mercury, .000181.

3. The same liquid often has different coefficients at different temperatures; that is, the expansion is irregular. Thus, if the coefficient of alcohol is obtained between 0° and 60° C., instead of between 0° and 10° C., it is .0013 instead of .0011.

The coefficient of mercury, however, is very nearly constant through a wide range of temperature, which indeed might have been inferred from the fact that mercury thermometers agree so well with gas thermometers.

165. Method of measuring the expansion coefficients of liquids. One of the most convenient and common methods of measuring the coefficients of liquids is to place them in bulbs of known volume, provided with capillary necks of known diameter, like that shown in Fig. 149, and then to watch the rise of the liquid in the neck for a given rise in temperature. A certain allowance must be made for the expansion of the bulb, but this can readily be done if the coefficient of expansion of the substance of which the bulb is made is known.

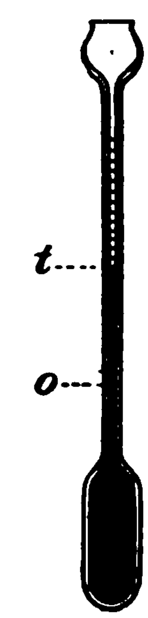


FIG. 149. Bulb for investigating expansions of liquids

166. Maximum density of water. When water is treated in the way described in the preceding paragraph, it reaches its lowest position in the stem at 4° C. As

the temperature falls from that point down to 0° C., water exhibits the peculiar property of *expanding* with a *decrease* in temperature.

We learn, therefore, that *water has its maximum density at a temperature of 4° C.*

167. The cooling of a lake in winter. The preceding paragraph makes it easy to understand the cooling of any large body of water with the approach of winter. The surface layers are first cooled and contract. Hence, being then heavier than the lower layers, they sink and are replaced by the warmer water from beneath. This process of cooling at the surface, and sinking, goes on until the whole body of water has reached a temperature of 4° C. After this condition has been reached, further cooling of the surface layers makes them *lighter* than the water beneath, and they now remain on top until they freeze. Thus, before any ice whatever can form on the surface of a lake, the whole mass of water to the very bottom must be cooled to 4° C. This is why it requires a much longer and more severe period of cold to freeze deep bodies of water than shallow ones. Further, since the circulation described above ceases at 4° C., practically all of the unfrozen water will be at 4° C. even in the coldest weather. Only the water which is in the immediate neighborhood of the ice will be lower than 4° C. This fact is of vital importance in the preservation of aquatic life.

168. Expansion of solids. The proofs of expansion of solids with an increase in temperature may be seen on every side. Railroad rails are laid with spaces between their ends so that they may expand during the heat of summer without crowding each other out of place. Wagon tires are made smaller than the wheels which they are to fit. They are then heated until they become large enough to be driven on, and in cooling they shrink again and thus grip the wheels with

immense force. A common lecture-room demonstration of expansion is the following:

Let the ball B, which when cool just slips through the ring R, be heated in a Bunsen flame. It will now be found too large to pass through the ring; but if the ring is heated, or if the ball is again cooled, it will pass through easily (see Fig. 150).

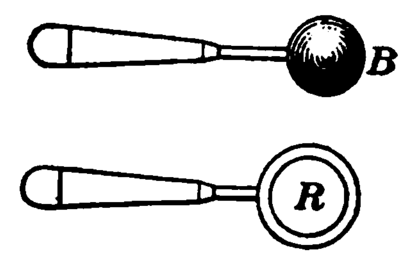


FIG. 150. Expansion of solids

If the expansion of gases and liquids is due to the increase in the average kinetic energy of agitation of their molecules, the foregoing experiments with solids must clearly be given a similar interpretation. In a word, then, the temperature of a given substance, be it solid, liquid, or gas, is determined by the average kinetic energy of agitation of its molecules.

169. Linear coefficients of expansion of solids. It is often more convenient to measure the increase in *length* of one edge of an expanding solid than to measure its increase in *volume*. *The ratio between the increase in length per degree rise in temperature and the total length is called the linear coefficient of expansion of the solid.* Thus, if l_1 represent the length of a bar at $t_1°$, and l_2 its length at $t_2°$, the equation which defines the linear coefficient k is

$$k = \frac{\frac{l_2 - l_1}{t_2 - t_1}}{l_1} = \frac{l_2 - l_1}{l_1 (t_2 - t_1)}. \qquad (5)$$

The linear coefficients of a few common substances are given in the following table:

Aluminium	.000023	Gold	.000014	Silver	.000019
Brass	.000019	Iron	.000012	Steel	.000013
Copper	.000017	Lead	.000029	Tin	.000023
Glass	.000009	Platinum	.000009	Zinc	.000030

Applications of Expansion

170. Compensated pendulum. Since a long pendulum vibrates more slowly than a short one, the expansion of the rod which carries the pendulum bob causes an ordinary clock to run too slowly in summer, and its contraction causes it to run too fast in winter. For this reason very accurate clocks are provided with *compensated* pendulums, which are so constructed that the distance of the bob beneath the point of support is independent of the temperature. This is accomplished by suspending the bob, by means of two sets of rods of different material, in such a way that the expansion of one set raises the bob, while the expansion of the other set lowers it. Such a pendulum is shown in Fig. 151. The expansion of the iron rods *b*, *d*, *e*, and *i* tends to lower the bob, while that of the copper rods *c* tends to raise it. In order to produce complete compensation it is only necessary to make the total lengths of iron and copper rods inversely proportional to the coefficients of expansion of iron and copper.

Fig. 151. The compensated pendulum

171. Compensated balance wheel. In the balance wheel of an accurate watch (Fig. 152) another application of the unequal expansion of metals is made. Increase in temperature both increases the radius of the wheel and weakens the elasticity of the spring which controls it. Both of these effects tend to make the watch lose time. This tendency may be counteracted by bringing the mass of the rotating parts in toward

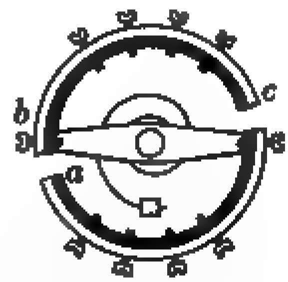


Fig. 152. The compensated balance wheel

the center of the wheel. This is accomplished by making the arcs *bc* of metals of different expansion coefficients, the inner

FIG. 153

FIG. 154

Unequal expansion of metals

metal, shown in black in the figure, having the smaller coefficient. The free ends of the arcs are then sufficiently pulled in by a rise in temperature to counteract the retarding effects.

The principle is precisely the same as that which finds simple illustration in the compound bar shown in Fig. 153. This bar consists of two strips, one of brass and one of iron, riveted together. When the bar is placed edgewise in a Bunsen flame, so that both metals are heated equally, it will be found to bend in such a way that the more expansible metal, namely, the brass, is on the outside of the curve, as shown in Fig. 154. When it is cooled with snow or ice, it bends in the opposite direction.

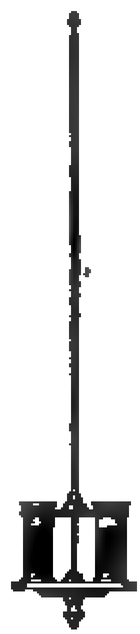


FIG. 155. The thermostat

The common thermostat (Fig. 155) is precisely such a bar, which is arranged so as to open the drafts by closing an electrical circuit at *a* when it is too cold, and to close the drafts by making contact at *b* when it is too warm.

FIG. 156

QUESTIONS AND PROBLEMS

1. Why is the water at the bottom of a lake usually colder than that at the top? Why is the water at the bottom of very deep mountain lakes in some instances observed to be at 4° C. the whole year round, while that at the top varies from 0° C. to quite warm?

2. Give three reasons why mercury is a better liquid to use in thermometers than water.

3. Why is a thick tumbler more likely to break when hot water is poured into it than a thin one?

4. Pendulums are often compensated by using cylinders of mercury, as in Fig. 156. Explain.

5. The steel cable from which Brooklyn Bridge hangs is more than a mile long. By how many feet does a mile of its length vary between a winter day when the temperature is $-20°$ C. and a summer day when it is $30°$ C.?

6. If a surveyor's steel tape is exactly 100 ft. long at $20°$ C., how much too short would it be at $0°$ C.?

7. A certain glass flask is graduated to hold 1000 cc. at $15°$ C. How many cubic centimeters will the same flask hold at $40°$ C., the coefficient of cubical expansion of glass being .000025?

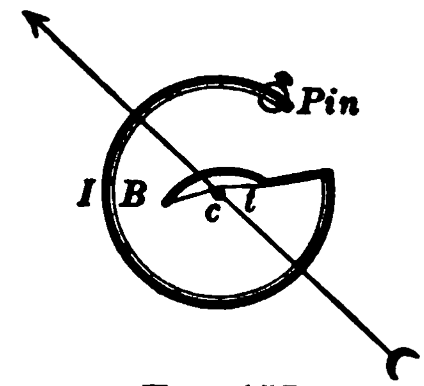


FIG. 157

8. The dial thermometer is a compound bar (Fig. 157) with iron on the outside and brass on the inside. A thread *t* is wound about the central cylinder *c*. Explain the action.

9. Why may a glass stopper sometimes be loosened by pouring hot water on the neck of a bottle?

10. A metal rod 230 cm. long expanded 2.75 mm. in being raised from 0°C. to 100°C. Find its coefficient of linear expansion.

11. The changes in temperature to which long lines of steam pipes are subjected make it necessary to introduce "expansion joints." These joints consist of brass collars fitted tightly by means of packing over the separated ends of two adjacent lengths of pipe. If the pipe is of iron, and such a joint is inserted every 200 ft., and if the range of temperature which must be allowed for is from $-30°$C. to $125°$C., what is the minimum play which must be allowed for at each expansion joint?

12. Show from equation 5, p. 140, that linear coefficient of expansion may be defined as *increase in length per unit length per degree.*

CHAPTER IX

WORK AND HEAT ENERGY

FRICTION

172. Friction always results in wasted work. All of the experiments mentioned in Chapter VII were so arranged that *friction* could be neglected or eliminated. So long as this condition was fulfilled it was found that the result of universal experience could be stated thus: *The work done by the acting force is equal to the sum of the kinetic and potential energies stored up.*

But wherever friction is present this law is found to be inexact, for the work of the acting force is then always somewhat greater than the sum of the kinetic and potential energies stored up. If, for example, a block is pulled over the horizontal surface of a table, at the end of the motion no velocity has been imparted to the block, and hence no kinetic energy has been stored up. Further, the block has not been lifted nor put into a condition of elastic strain, and hence no potential energy has been communicated to it. We cannot in any way obtain from the block more work after the motion than we could have obtained before it was moved. It is clear, therefore, that all of the work which was done in moving the block against the friction of the table was *wasted work.* Experience shows that, in general, where work is done against friction it can never be regained. Before considering what becomes of this wasted work we shall consider some of the factors on which friction depends and some of the laws which are found by experiment to hold in cases in which friction occurs.

173. Coefficient of friction. It is found that if F represents the force parallel to a plane which is necessary to maintain uniform motion in a body which is pressed against the plane with a force F', then, for small velocities, the ratio $\frac{F}{F'}$ depends only on the nature of the surfaces in contact, and not at all on the area or on the velocity of the motion. The ratio $\frac{F}{F'}$ is called the *coefficient of friction* for the given materials. Thus (Fig. 158), if F is 300 g. and F' is 800 g., the coefficient of friction is $\frac{300}{800} = .375$. The coefficient of iron on iron is about .2; of oak on oak, about .4.

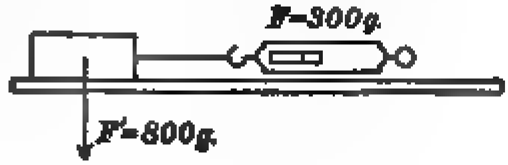


FIG. 158. The ratio of F to F' is the coefficient of friction

174. Rolling friction. The chief cause of sliding friction is the interlocking of minute projections. When a round solid *rolls* over a smooth surface, the frictional resistance is generally much less than when it slides; for example, the coefficient of friction of cast-iron wheels rolling on iron rails may be as low as .002, that is, $\frac{1}{100}$ of the sliding friction

(1) (2)

FIG. 159. Friction in bearings

(1) Common bearing; (2) ball bearing

of iron on iron. This means that a pull of 1 pound will keep a 500-pound car in motion. Sliding friction is not, however, entirely dispensed with in ordinary wheels, for although the rim of the wheel rolls on the track, the axle slides continuously at some point c (Fig. 159, (1)) upon the surface of the journal. Journals are frequently lined with brass or Babbitt metal, since this still further lowers the coefficient.

The great advantage of the ball bearing (Fig. 159, (2)) is that the sliding friction in the hub is almost completely replaced by rolling friction. The manner in which ball bearings are used in a bicycle

pedal is illustrated in Fig. 160. The free-wheel ratchet is shown in Fig. 161. The pawls *a* and *b* enable the pedals and chain wheel *W* to stop while the rear axle continues to revolve. Roller bearings are shown in Fig. 162. Oils and greases prevent rapid wear of bearings by lessening friction.

FIG. 160. The bicycle pedal FIG. 161. Free-wheel ratchet

175. Fluid friction. When a solid moves through a fluid, as when a bullet moves through the air or a ship through the water, the resistance encountered is not at all independent of velocity, as in the case of solid friction, but increases for slow speeds nearly as the square of the velocity, and for high speeds at a rate considerably greater. This explains why it is so expensive to run a fast train; for the resistance of the air, which is a small part of the total resistance so long as the train is moving slowly, becomes the predominant factor at high speeds. The resistance offered to steamboats running at high speeds is usually considered to increase as the cube of the velocity. Thus, the *Cedric*, of the White Star Line, having a speed of 17 knots, has a horse power of 14,000 and a total weight, when loaded, of about 38,000 tons, while the *Mauretania*, of the Cunard Line, having a speed of 25 knots, has engines of 70,000 horse power, although the total weight when loaded is only 32,500 tons.

FIG. 162. Roller bearings of automobile front wheel

QUESTIONS AND PROBLEMS

1. Mention three ways of lessening friction in machinery.

2. In what respects is friction an advantage, and in what a disadvantage, in everyday life? Could we get along without it?

3. Why is a stream swifter at the center than at the banks?

4. Why does a team have to keep pulling after a load is started?

5. Why is sand often placed on a track in starting a heavy train?

6. In what way is friction an advantage in lifting buildings with a jackscrew? In what way is it a disadvantage?

7. A smooth block is $10 \times 8 \times 3$ in. Compare the distances which it will slide when given a certain initial velocity on smooth ice if resting first, on a 10×8 face; second, on a 10×3 face; third, on an 8×3 face.

8. What is the coefficient of friction of brass on brass if a force of 25 lb. is required to maintain uniform motion in a brass block weighing 200 lb. when it slides horizontally on a brass bed?

9. The coefficient of friction between a block and a table is .3. What force will be required to keep a 500-gram block in uniform motion?

EFFICIENCY

176. Definition of efficiency. Since it is only in an ideal machine that there is no friction, in all actual machines the work done by the acting force always exceeds, by the amount of the work done against friction, the amount of potential and kinetic energy stored up. We have seen that the former is wasted work in the sense that it can never be regained. Since the energy stored up represents work which can be regained, it is termed *useful work.* In most machines an effort is made to have the useful work as large a fraction of the total work expended as possible. *The ratio of the useful work to the total work done by the acting force is called the* EFFICIENCY *of the machine.* Thus

$$\text{Efficiency} = \frac{\text{Useful work accomplished}}{\text{Total work expended}}. \qquad (1)$$

Thus, if in the system of pulleys shown in Fig. 116 it is necessary to add a weight of 50 g. at E in order to pull up slowly an added weight of 240 g. at R, the work done by the 50 g. while E is moving over 1 cm. will be 50×1 g. cm. The useful work accomplished in the same time is $240 \times \frac{1}{6}$ g. cm. Hence the efficiency is equal to $\frac{240 \times \frac{1}{6}}{50 \times 1} = \frac{4}{5} = 80\%$.

177. Efficiencies of some simple machines. In simple levers the friction is generally so small as to be negligible; hence the efficiency of such machines is approximately 100%. When

inclined planes are used as machines, the friction is also small, so that the efficiency generally lies between 90% and 100%. The efficiency of the commercial block and tackle (Fig. 116), with several movable pulleys, is usually considerably less, varying between 40% and 60%. In the jackscrew there is necessarily a very large amount of friction, so that although the mechanical advantage is enormous, the efficiency is often as low as 25%. The differential pulley of Fig. 136 has also a very high mechanical advantage with a very small efficiency. Gear wheels such as those shown in Fig. 134, or chain gears such as those used in bicycles, are machines of comparatively high efficiency, often utilizing between 90% and 100% of the energy expended upon them.

178. Efficiency of overshot water wheels. The overshot water wheel (Fig. 163) utilizes chiefly the potential energy of the water at *S*, for the wheel is turned by the weight of the water in the buckets. The work expended on the wheel per second, in foot pounds or gram centimeters, is the product of the weight of the water which passes over it per second by the distance through which it falls. The efficiency is the work which the wheel can accomplish in a second divided by this quantity. Such wheels are very common in mountainous regions, where it is easy to obtain considerable fall but where the streams carry a small *volume* of water. The efficiency is high, being often between 80% and 90%. The loss is due not only to the friction in the bearings and gears (see *C*) but also to the fact that some of the water is spilled from the buckets or passes over without entering them at all. This may still be regarded as a frictional loss, since the energy disappears in internal friction when the water strikes the ground.

Fig. 163. Overshot water wheel

179. Efficiency of undershot water wheels. The old-style undershot wheel (Fig. 164) — so common in flat countries, where there is little fall but an abundance of water — utilizes only the kinetic energy of the water

running through the race from A. It seldom transforms into useful work more than 25% or 30% of the potential energy of the water above the dam. There are, however, certain modern forms of undershot wheel which are extremely efficient. For example, the *Pelton wheel* (Fig. 165), developed since 1880 and now very commonly used for small-power purposes in cities supplied with waterworks, sometimes has an efficiency as high as 83%. The water is delivered from a nozzle O against cup-shaped buckets arranged as in the figure. At the Big Creek development in California, Pelton wheels 94 inches in diameter are driven by water coming with a velocity of 350 feet per second (how many miles per hour?) through nozzles 6 inches in diameter. The head of water is here 1900 ft.

FIG. 164. The undershot wheel

180. Efficiency of water turbines. The turbine wheel was invented in France in 1833 and is now used more than any other form of water wheel. It stands completely under water in a case at the bottom of a *turbine pit*, rotating in a horizontal plane. Fig. 166 shows the method of installing a turbine at Niagara. C is the outer case into which the water enters from the penstock p. Fig. 167, (1), shows the outer case with contained turbine; Fig. 167, (2), is the inner case, in which are the fixed guides G, which direct the water at the most advantageous angle against the blades of the wheel inside; Fig. 167, (3), is the wheel itself; and Fig. 167, (4), is a section of wheel and inner case, showing how the water enters through the guides and impinges upon the blades W. The spent water simply falls down from the blades into the tailrace T (Fig. 166). The amount of water which passes through the turbine can be controlled by means of the rod P (Fig. 167, (1)), which can be turned so as to increase or decrease the size of the openings between the guides G (Fig. 167, (2)). The energy expended upon the turbine per second is the product of the mass of water which passes through it by the height of the turbine pit. Efficiencies as high as 90% have been attained with such wheels.

FIG. 165. The Pelton water wheel

One of the largest turbines in existence is operated by the Puget Sound Power Co. It develops 25,000 horse power under a 440-foot head of water.

(1)

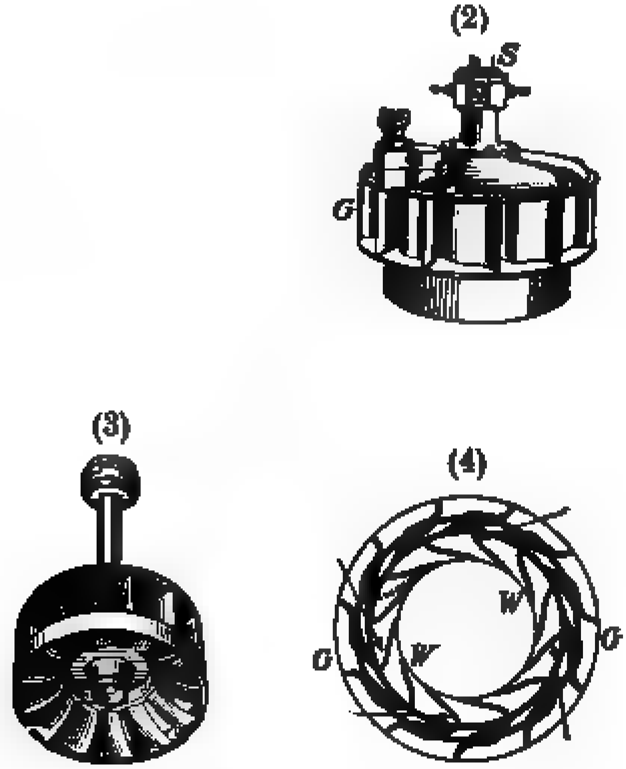


Fig. 166. A turbine installed

Fig. 167. The turbine wheel

(1) Outer case; (2) inner case; (3) rotating part; (4) section

QUESTIONS AND PROBLEMS

1. Why is the efficiency of the jackscrew low and that of the lever high?

2. Find the efficiency of a machine in which an effort of 12 lb. moving 5 ft. raises a weight of 25 lb. 2 ft.

3. What amount of work was done on a block and tackle having an efficiency of 60% when by means of it a weight of 750 lb. was raised 50 ft.?

4. A force pump driven by a 1-horse-power engine lifted 4 cu. ft. of water per minute to a height of 100 ft. What was the efficiency of the pump?

5. If it is necessary to pull on a block and tackle with a force of 100 lb. in order to lift a weight of 300 lb., and if the force must move 6 ft. to raise the weight 1 ft., what is the efficiency of the system?

6. If the efficiency had been 65%, what force would have been necessary in the preceding problem?

7. The Niagara turbine pits are 136 ft. deep, and their average horse power is 5000. Their efficiency is 85%. How much water does each turbine discharge per minute?

Mechanical Equivalent of Heat *

181. What becomes of wasted work? In all the devices for transforming work which we have considered we have found that on account of frictional resistances a certain per cent of the work expended upon the machine is wasted. The question which at once suggests itself is, What becomes of this wasted work? The following familiar facts suggest an answer. When two sticks are vigorously rubbed together, they become hot; augers and drills often become too hot to hold; matches are ignited by friction; if a strip of lead is struck a few sharp blows with a hammer, it is appreciably warmed. Now, since we learned in Chapter VIII that, according to modern notions, increasing the temperature of a body means simply increasing the average velocity of its molecules, and therefore their average kinetic energy, the above facts point strongly to the conclusion that in each case the mechanical energy expended has been simply transformed into the energy of molecular motion. This view was first brought into prominence in 1798 by Benjamin Thompson, Count Rumford, an American by birth, who was led to it by observing that in the boring of cannon heat was continuously developed. It was first carefully tested by the English physicist James Prescott Joule (see opposite p. 122) (1818–1889) in a series of epoch-making experiments extending from 1842 to 1870. In order to understand these experiments we must first learn how heat quantities are measured.

* This subject should be preceded by a laboratory experiment upon the "law of mixtures," and either preceded or accompanied by experiments upon specific heat and mechanical equivalent. See authors' Manual, Experiments 18, 19, and 20.

182. Units of heat; the calorie and the British thermal unit. *The calorie is the amount of heat that is required to raise the temperature of 1 gram of water through 1° C., and the British thermal unit (B. T. U.) is the amount of heat that is required to raise the temperature of 1 pound of water through 1° F.* (One B.T.U. = 252 cal.) Thus, when a hundred grams of water has its temperature raised 4° C. we say that four hundred calories of heat have entered the water. Similarly, when a hundred grams of water has its temperature lowered 10° C. we say that a thousand calories have passed out of the water. If, then, we wish to measure, for instance, the amount of heat developed in a lead bullet when it strikes against a target, we have only to let the spent bullet fall into a known weight of water and to measure the number of degrees through which the temperature of the water rises. The product of the number of grams of water by its rise in temperature is, then, by definition, the number of calories of heat which have passed into the water.

It will be noticed that in the above definition we make no assumption whatever as to *what heat is*. Previous to the nineteenth century physicists generally held it to be an invisible, weightless fluid, the passage of which into or out of a body caused it to grow hot or cold. This view accounts well enough for the heating which a body experiences when it is held in contact with a flame or other hot body, but it has difficulty in explaining the heating produced by rubbing or pounding. Rumford's view accounts easily for this, as we have seen, while it accounts no less easily for the heating of cold bodies by contact with hot ones; for we have only to think of the hotter and therefore more energetic molecules of the hot body as communicating their energy to the molecules of the colder body in much the same way in which a rapidly moving billiard ball transfers part of its kinetic energy to a more slowly moving ball against which it strikes.

A UNITED STATES DREADNAUGHT PASSING THROUGH THE FAMOUS CULEBRA CUT OF THE PANAMA CANAL

A of the *Tennessee* type, the largest now in use, has a displacement of over 32,500 tons, a h, and develops a speed of about 21 knots. Her armor above the water line at her most vit while that of the main turrets is 18 inches thick. She carries twelve 14-inch guns which throw 1400-pound projectiles effectively against an enemy ship 10 or 12 miles distant. The crew numbers about 1000 men and more than 100 officers. One shot from a 14-inch gun possesses the energy equivalent of a volley from 60,000 muskets. The cost of a modern dreadnaught is $22,000,000. At present the largest one is the electrically driven superdreadnaught *Tennessee*

© Underwood & Underwood

THE VICKERS-VIMY AIRPLANE

The first nonstop transatlantic airplane flight was made on June 14, 1919, from St. John's, Newfoundland, to Clifden, Ireland, — a distance of 1890 miles. This historic flight — the longest ever made — was accomplished in fifteen hours and fifty-seven minutes, through fog and sleet, at an average speed of 118.5 miles per hour, — a feat which won the $50,000 prize which had been offered for nearly five years by the London *Daily Mail*. The plane was driven by two 360-horse-power Rolls-Royce motors and carried 865 gallons of gasoline. It was piloted by Capt. John Alcock and navigated by Lieut. Arthur W. Brown. This airplane had a wing spread of 67 feet and a length of 42 feet 8 inches

183. Joule's experiment on the heat developed by friction. Joule argued that if the heat produced by friction etc. is indeed merely mechanical energy which has been transferred to the molecules of the heated body, then the same number of calories must always be produced by the disappearance of a given amount of mechanical energy. And this must be true, no matter whether the work is expended in overcoming the friction of wood on wood, of iron on iron, in percussion, in compression, or in any other conceivable way. To see whether or not this was so he caused mechanical energy to disappear in as many ways as possible and measured in every case the amount of heat developed.

In his first experiment he caused paddle wheels to rotate in a vessel of water by means of falling weights *W* (Fig. 168). The amount of work done by gravity upon the weights in causing them to descend through any distance *d* was equal to their weight *W* times this distance. If the weights descended slowly and uniformly, this work was all expended in overcoming the resistance of the water to the motion of the paddle wheels through it; that is, it was wasted in eddy currents in the water. Joule measured the rise in the temperature of the water and found that the mean of his three best trials gave 427 gram meters as the amount of work required to develop enough heat to raise a gram of water one degree. This value, confirmed by modern experiments, is now generally accepted as correct. He then repeated the experiment, substituting mercury for water, and obtained 425 gram meters as the work necessary to produce a calorie of heat. The difference between these numbers is less than was to have been expected from the unavoidable errors in the observations. He then devised an arrangement in which the heat was developed by the friction of iron on iron, and again obtained 425.

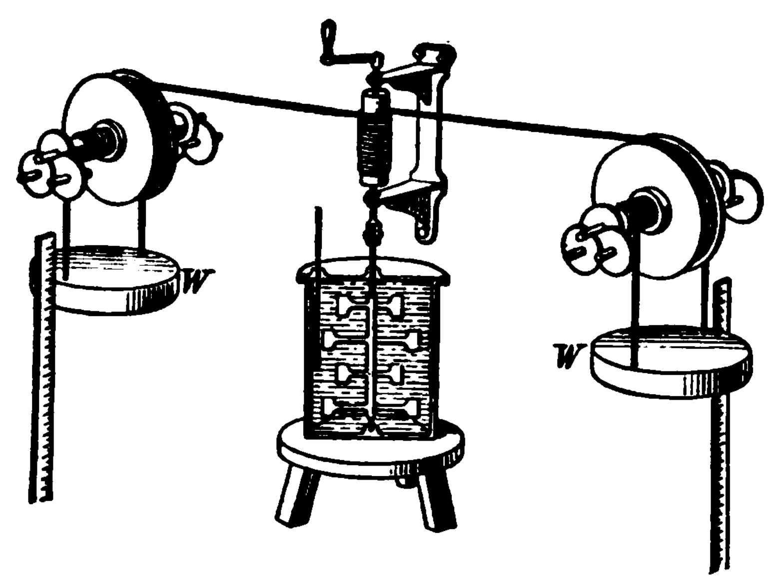


FIG. 168. Joule's first experiment on the mechanical equivalent of heat

184. Heat produced by collision. A Frenchman named Hirn was the first to make a careful determination of the relation between the heat developed by *collision* and the kinetic energy which disappears. He allowed a steel cylinder to fall through a known height and crush a lead ball by its impact upon it. The amount of heat developed in the lead was measured by observing the rise in temperature of a small amount of water into which the lead was quickly plunged. As the mean of a large number of trials he also found that 425 gram meters of energy disappeared for each calorie of heat that appeared.

185. Heat produced by the compression of a gas. Another way in which Joule measured the relation between heat and work was by compressing a gas and comparing the amount of work done in the compression with the amount of heat developed.

Every bicyclist is aware of the fact that when he inflates his tires the pump grows hot. This is due partly to the friction of the piston against the walls, but chiefly to the fact that the downward motion of the piston is transferred to the molecules which come in contact with it, so that the velocity of these molecules is increased. The principle is precisely the same as that involved in the velocity communicated to a ball by a bat. If the bat is held rigidly fixed and a ball thrown against it, the ball rebounds with a certain velocity; but if the bat is moving rapidly forward to meet the ball, the latter rebounds with a much greater velocity. So the molecules which in their natural motions collide with an advancing piston rebound with greater velocity than they would if they had impinged upon a fixed wall. This increase in the molecular velocity of a gas on compression is so great that when a mass of gas at 0° C. is compressed to one half its volume, the temperature rises to 87° C.

The effect may be strikingly illustrated by the fire syringe (Fig. 169). Let a few drops of carbon bisulphide be placed on a small bit of cotton, dropped to the bottom of the tube A, and then removed; then let the

piston B be inserted and very suddenly depressed. Sufficient heat will be developed to ignite the vapor, and a flash will result. (If the flash does not result from the first stroke, withdraw the piston completely, then reinsert, and compress again.)

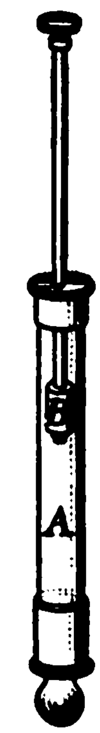


FIG. 169. The fire syringe

To measure the heat of compression Joule surrounded a small compression pump with water, took 300 strokes on the pump, and measured the rise in temperature of the water. As the result of these measurements he obtained 444 gram meters as the mechanical equivalent of the calorie. The experiment, however, could not be performed with great exactness.

Joule also measured the converse effect, namely, the cooling produced in a gas which is pushing forward a piston and thus *doing work.* He obtained 437 gram meters.

186. Significance of Joule's experiments. Joule made three other determinations of the relation between heat and work by methods involving electrical measurements. He published as the mean of all his determinations 426.4 gram meters as the mechanical equivalent of the calorie. But the value of his experiments does not lie primarily in the accuracy of the final results, but rather in the proof which they for the first time furnished that *whenever a given amount of work is wasted, no matter in what particular way this waste occurs, the same definite amount of heat always appears.*

The most accurate determination of the mechanical equivalent of heat was made by Rowland (see opposite p. 358) (1848–1901) in 1880. *He obtained 427 gram meters* (4.19×10^7 *ergs*). We shall generally take it as 42,000,000 ergs. *The mechanical equivalent of 1 B. T. U. is 778 foot pounds.*

187. The conservation of energy. We are now in a position to state the law of all machines in its most general form, that is, in such a way as to include even the cases where friction

is present. It is: *The work done by the acting force is equal to the sum of the kinetic and potential energies stored up plus the mechanical equivalent of the heat developed.*

In other words, *whenever energy is expended on a machine or device of any kind, an exactly equal amount of energy always appears either as useful work or as heat.* The useful work may be represented in the potential energy of a lifted mass, as when water is pumped up to a reservoir; or in the kinetic energy of a moving mass, as when a stone is thrown from a sling; or in the potential energies of molecules whose positions with reference to one another have been changed, as when a spring has been bent; or in the molecular potential energy of chemically separated atoms, as when an electric current separates a compound substance. The *wasted* work always appears in the form of increased molecular motion, that is, in the form of heat. This important generalization has received the name of the *Principle of the Conservation of Energy.* It may be stated thus: *Energy may be transformed, but it can never be created or destroyed.*

188. Perpetual motion. In all ages there have been men who have spent their lives in trying to invent a machine out of which work could be continually obtained, without the expenditure of an equivalent amount of work upon it. Such devices are called perpetual-motion machines. The possibility of the existence of such a device is absolutely denied by the statement of the principle of the conservation of energy. For only in case there is no heat developed, that is, in case there are no frictional losses, can the work taken out be equal to the work put in, and in no case can it be greater. Since, in fact, there are always some frictional losses, the principle of the conservation of energy asserts that it is impossible to make a machine which will keep itself running forever, even though it does no useful work; for no matter how much kinetic or potential energy is imparted to the machine to begin with, there

must always be a continual drain upon this energy to overcome frictional resistances, so that as soon as the wasted work has become equal to the initial energy, the machine must stop.

The principle of the conservation of energy has now gained universal recognition and has taken its place as the corner stone of all physical science.

189. Transformations of energy in a power plant. The transformations of energy which take place in any power plant, such as that at Niagara, are as follows: The energy first exists as the potential energy of the water at the top of the falls. This is transformed in the turbine pits into the kinetic energy of the rotating wheels. These turbines drive dynamos in which there is a transformation into the energy of electric currents. These currents travel on wires as far as Syracuse, 150 miles away, where they run street cars and other forms of motors. The principle of conservation of energy asserts that the work which gravity did upon the water in causing it to descend from the top to the bottom of the turbine pits is exactly equal to the work done by all the motors, plus the heat developed in all the wires and bearings and in the eddy currents in the water.

Let us next consider where the water at the top of the falls obtained its potential energy. Water is being continually evaporated at the surface of the ocean by the sun's heat. This heat imparts sufficient kinetic energy to the molecules to enable them to break away from the attractions of their fellows and to rise above the surface in the form of vapor. The lifted vapor is carried by winds over the continents and precipitated in the form of rain or snow. Thus the potential energy of the water above the falls at Niagara is simply transformed heat energy of the sun. If in this way we analyze any available source of energy at man's disposal, we find in almost every case that it is directly traceable to the sun's heat as its source. Thus, the energy contained in coal is simply the energy of separation of the oxygen and carbon which were separated in the processes of growth. This separation was effected by the sun's rays.

The earth is continually receiving energy from the sun at the rate of 342,000,000,000,000 horse power, or about a quarter of a million horse power per inhabitant. We can form some conception of the enormous amount of energy that the sun radiates in the form of heat by reflecting that the amount received by the earth is not more than $\frac{1}{2,000,000,000}$

of the total given out. Of the amount received by the earth not more than $\frac{1}{1000}$ part is stored up in animal and vegetable life and lifted water. This is practically all of the energy which is available on the earth for man's use.

QUESTIONS AND PROBLEMS

1. Show that the energy of a waterfall is merely transformed solar energy.
2. Analyze the transformations of energy which occur when a bullet is fired vertically upward.
3. Meteorites are small, cold bodies moving about in space. Why do they become luminous when they enter the earth's atmosphere?
4. The Niagara Falls are 160 ft. high. How much warmer is the water at the bottom of the falls than at the top?
5. How many B. T. U. are required to warm 10 lb. of water from freezing to boiling?
6. Two and a half gallons of water (= 20 lb.) were warmed from 68° F. to 212° F. If the heat energy put into the water could all have been made to do useful work, how high could 10 tons of coal have been hoisted?

Specific Heat

190. Definition of specific heat. When we experiment upon different substances, we find that it requires wholly different amounts of heat energy to produce in one gram of mass one degree of change in temperature.

Let 100 g. of lead shot be placed in one test tube, 100 g. of bits of iron wire in another, and 100 g. of aluminium wire in a third. Let them all be placed in a pail of boiling water for ten or fifteen minutes, care being taken not to allow any of the water to enter any of the tubes. Let three small vessels be provided, each of which contains 100 g. of water at the temperature of the room. Let the heated shot be poured into the first beaker, and after thorough stirring let the rise in the temperature of the water be noted. Let the same be done with the other metals. The aluminium will be found to raise the temperature about twice as much as the iron, and the iron about three times as much as the lead. Hence, since the three metals have cooled through approximately the same number of degrees, we must conclude that about six times as much heat has passed out of the aluminium as out of the lead; that is, each gram of aluminium in cooling 1° C. gives out about six times as many calories as a gram of lead.

The number of calories taken up by 1 gram of a substance when its temperature rises through 1° C., or given up when it falls through 1° C., is called the specific heat of that substance.

It will be seen from this definition, and the definition of the calorie, that the specific heat of water is 1.

191. Determination of specific heat by the method of mixtures. The preceding experiments illustrate a method for measuring accurately the specific heats of different substances; for, in accordance with the principle of the conservation of energy, when hot and cold bodies are mixed, as in these experiments, so that heat energy passes from one to the other, *the gain in the heat energy of one must be just equal to the loss in the heat energy of the other.*

This method is by far the most common one for determining the specific heats of substances. It is known as the *method of mixtures.*

Suppose, to take an actual case, that the initial temperature of the shot used in § 190 was 95° C. and that of the water 19.7°, and that, after mixing, the temperature of the water and shot was 22°. Then, since 100 g. of water has had its temperature raised through 22° − 19.7° = 2.3°, we know that 230 calories of heat have entered the water. Since the temperature of the shot fell through 95° − 22° = 73°, the number of calories given up by the 100 g. of shot in falling 1° was $\frac{230}{73} = 3.15$. Hence the specific heat of lead, that is, *the number of calories of heat given up by 1 gram of lead when its temperature falls 1° C.*, is $\frac{3.15}{100} = .0315$.

Or, again, we may work out the problem algebraically as follows: Let x equal the specific heat of lead. Then the number of calories which come out of the shot is *its mass times its specific heat times its change in temperature*, that is, $100 \times x \times (95 - 22)$; and, similarly, the number which enter the water is the same, namely, $100 \times 1 \times (22 - 19.7)$. Hence we have

$$100\,(95 - 22)\,x = 100\,(22 - 19.7), \quad \text{or} \quad x = .0315.$$

By experiments of this sort the specific heats of some of the common substances have been found to be as follows:

TABLE OF SPECIFIC HEATS

Aluminium	.218	Iron	.113
Brass	.094	Lead	.0315
Copper	.095	Mercury	.0333
Glass	.2	Platinum	.032
Gold	.0316	Silver	.0568
Ice	.504	Zinc	.0935

QUESTIONS AND PROBLEMS

1. A barrelful of tepid water, when poured into a snowdrift, melts much more snow than a cupful of boiling water does. Which has the greater quantity of heat?

2. Why is a liter of hot water a better foot warmer than an equal volume of any substance in the preceding table?

3. The specific heat of water is much greater than that of any other liquid or of any solid. Explain how this accounts for the fact that an island in mid-ocean undergoes less extremes of temperature than an inland region.

4. How many calories are required to heat a laundry iron weighing 3 kg. from 20° C. to 130° C.?

5. How many B. T. U. are required to warm a 6-pound laundry iron from 75° F. to 250° F.?

6. If 100 g. of mercury at 95° C. are mixed with 100 g. of water at 15° C., and if the resulting temperature is 17.6° C., what is the specific heat of mercury?

7. If 200 g. of water at 80° C. are mixed with 100 g. of water at 10° C., what will be the temperature of the mixture? (Let x equal the final temperature; then $100(x-10)$ calories are gained by the cold water, while $200(80-x)$ calories are lost by the hot water.)

8. What temperature will result if 400 g. of aluminium at 100° C. are placed in 500 g. of water at 20° C.?

9. Eight pounds of water were placed in a copper kettle weighing 2.5 lb. How many B. T. U. are required to heat the water and the kettle from 70° F. to 212° F.? If 4.3 cu. ft. of gas was used to do this, and if each cubic foot of gas on being burned yields 625 B. T. U., what is the efficiency of the heating apparatus?

10. If a solid steel projectile were shot with a velocity of 1000 m. (3048 ft.) per second against an impenetrable steel target, and all the heat generated were to go toward raising the temperature of the projectile, what would be the amount of the increase?

CHAPTER X

CHANGE OF STATE

Fusion *

192. Heat of fusion. If on a cold day in winter a quantity of snow is brought in from out of doors, where the temperature is below 0° C. and placed over a source of heat, a thermometer plunged into the snow will be found to rise slowly until the temperature reaches 0° C., when it will become stationary and remain so during all the time the snow is melting, provided only that the contents of the vessel are continuously and vigorously stirred. As soon as the snow is all melted, the temperature will begin to rise again.

Since the temperature of ice at 0° C. is the same as the temperature of water at 0° C., it is evident from this experiment that when ice is being changed to water, the entrance of heat energy into it does not produce any change in the average kinetic energy of its molecules. This energy must therefore all be expended in pulling apart the molecules of the crystals of which the ice is composed, and thus reducing it to a form in which the molecules are held together less intimately, that is, to the liquid form. In other words, the energy which existed in the flame as the kinetic energy of molecular motion has been transformed, upon passage into the melting solid, into the potential energy of molecules which have been pulled apart against the force of their mutual attraction. *The number*

* This subject should be preceded by a laboratory exercise on the curve of cooling through the point of fusion, and followed by a determination of the heat of fusion of ice. See, for example, Experiments 21 and 22 of the authors' Manual.

of calories of heat energy required to melt one gram of any substance without producing any change in its temperature is called the heat of fusion of that substance.

193. Numerical value of heat of fusion of ice. Since it is found to require about 80 times as long for a given flame to melt a quantity of snow as to raise the melted snow through 1° C., we conclude that it requires about 80 calories of heat to melt 1 g. of snow or ice. This constant is, however, much more accurately determined by the method of mixtures. Thus, suppose that a piece of ice weighing 131 g. is dropped into 500 g. of water at 40° C., and suppose that after the ice is all melted the temperature of the mixture is found to be 15° C. The number of calories which have come out of the water is $500 \times (40 - 15) = 12{,}500$. But $131 \times 15 = 1965$ calories of this heat must have been used in raising the ice from 0° C. to 15° C. after the ice, by melting, became water at 0°. The remainder of the heat, namely, $12{,}500 - 1965 = 10{,}535$, must have been used in melting the 131 g. of ice. Hence the number of calories required to melt 1 g. of ice is $\frac{10535}{131} = 80.4$.

To state the problem algebraically, let $x =$ the heat of fusion of ice. Then we have

$$131\,x + 1965 = 12{,}500\text{; that is, } x = 80.4.$$

According to the most careful determinations the heat of fusion of ice is 80.0 *calories.*

194. Energy transformation in fusion. The heat energy that goes into a body to change it from the solid state to the liquid state no longer exists as heat within the liquid. It has *ceased to exist as heat energy at all*, having been transformed into *molecular potential energy*; that is, *the heat which disappears represents the work that was done in effecting the change of state*, and it is, therefore, the exact equivalent of the potential energy gained by the rearranged molecules. This is strictly in accord with the law of conservation of energy.

195. Heat given out when water freezes. Let snow and salt be added to a beaker of water until the temperature of the liquid mixture is as low as $-10°$ C. or $-12°$ C. Then let a test tube containing a thermometer and a quantity of pure water be thrust into the cold solution. If the thermometer is kept very quiet, the temperature of the water in the test tube will fall four or five or even ten degrees below 0° C. without producing solidification. But as soon as the thermometer is stirred, or a small crystal of ice is dropped into the neck of the tube, the ice crystals will form with great suddenness, and at the same time the thermometer will rise to 0° C., where it will remain until all the water is frozen.

The experiment shows in a very striking way that the process of freezing is a heat-evolving process. This was to have been expected from the principle of the conservation of energy; for *since it takes* 80 *calories of heat energy to turn a gram of ice at* 0° *C. into water at* 0° *C., this amount of energy must reappear when the water turns back to ice.*

196. Use made of energy transformations in melting and freezing. A refrigerator (Fig. 170) is a box constructed with double walls so as to make it difficult for heat to pass in from the outside. Ice is kept in the *upper* part of one compartment so as to cool the air at the top, which, because of its greater density when cool, settles and causes a circulation as indicated by the arrows. To melt each gram of ice 80 calories must be taken from the air and food within the refrigerator. If the ice did not melt, it would be worthless for use in refrigerators.

Fig. 170. A refrigerator

The heat given off by the freezing of water is often turned to practical account; for example, tubs of water are sometimes placed in vegetable cellars to prevent the vegetables from freezing. The effectiveness of this procedure is due to the fact that the temperature at which the vegetables freeze is slightly

lower than 0° C. As the temperature of the cellar falls the water therefore begins to freeze first, and in so doing evolves enough heat to prevent the temperature of the room from falling as far below 0° C. as it otherwise would.

It is partly because of the heat evolved by the freezing of large bodies of water that the temperature never falls so low in the vicinity of large lakes as it does in inland localities.

197. Melting points of crystalline substances. If a piece of ice is placed in a vessel of boiling water for an instant and then removed and wiped, it will not be found to be in the slightest degree warmer than a piece of ice which has not been exposed to the heat of the warm water. The melting point of ice is therefore a perfectly fixed, definite temperature, above which the ice can never be raised so long as it remains ice, no matter how fast heat is applied to it. All crystalline substances are found to behave exactly like ice in this respect, each substance of this class having its characteristic melting point. The following table gives the melting points of some of the commoner crystalline substances:

Mercury	−39°C.	Sulphur	114°C.	Silver	954°C.
Ice	0°C.	Tin	233°C.	Copper	1100°C.
Benzine	7°C.	Lead	330°C.	Cast iron	1200°C.
Acetic acid	17°C.	Zinc	433°C.	Platinum	1775°C.
Paraffin	54°C.	Aluminium	650°C.	Iridium	1950°C.

We may summarize the experiments upon melting points of crystalline substances in the two following laws:

1. *The temperatures of solidification and fusion are the same.*

2. *The temperature of the melting or solidifying substance remains constant from the moment at which melting or solidification begins until the process is completed.*

198. Fusion of noncrystalline, or amorphous, substances. Let the end of a glass rod be held in a Bunsen flame. Instead of changing suddenly from the solid to the liquid state, it will gradually grow softer

and softer until, if the rod is not too thick and the flame is sufficiently hot, a drop of molten glass will finally fall from the end of the rod.

If the temperature of the rod had been measured during this process, it would have been found to be continually rising. This behavior, so completely unlike that of crystalline substances, is characteristic of tar, wax, resin, glue, gutta-percha, alcohol, carbon, and in general of all amorphous substances. Such substances cannot be said to have any definite melting points at all, for they pass through all stages of viscosity both in melting and in solidifying. It is in virtue of this property that glass and other similar substances can be heated to softness and then molded or rolled into any desired shape.

199. Change of volume on solidifying. One has only to reflect that ice floats, or that bottles or crocks of water burst when they freeze, in order to know that water expands upon solidifying. In fact, 1 cubic foot of water becomes 1.09 cubic feet of ice, thus expanding more than one twelfth of its initial volume when it freezes. This may seem strange in view of the fact that the molecules are certainly more closely knit together in the solid than in the liquid state; but the strangeness disappears when we reflect that the molecules of water in freezing group themselves into crystals, and that this operation presumably leaves comparatively large free spaces between different crystals, so that, although groups of individual molecules are more closely joined than before, the total volume occupied by the whole assemblage of molecules is greater.

But the great majority of crystalline substances contract upon solidifying and expand upon liquefying. Water, antimony, bismuth, cast iron, and a few alloys containing antimony or bismuth are the chief exceptions. It is only from substances which expand, or which change in volume very little on solidifying, that sharp castings can be made; for it is clear that contracting substances cannot retain the shape of the mold. It is for this reason that gold and silver coins must be stamped

rather than cast. Any metal from which type is to be cast must be one which expands upon solidifying, for it need scarcely be said that perfectly sharp outlines are indispensable to good type. Ordinary type metal is an alloy of lead, antimony, and copper, which fulfills these requirements.

200. Effect of the expansion which water undergoes on freezing. If water were not unlike most substances in that it expands on freezing, many, if not all, of the forms of life which now exist on the earth would be impossible; for in winter the ice would sink in ponds and lakes as fast as it froze, and soon our rivers, lakes, and perhaps our oceans also would become solid ice.

The force exerted by the expansion of freezing water is very great. Steel bombs have been burst by filling them with water and exposing them on cold winter nights. One of the chief agents in the disintegration of rocks is the freezing and consequent expansion of water which has percolated into them.

201. Pressure lowers the melting point of substances which expand on solidifying. Since the outside pressure acting on the surface of a body tends to prevent its expansion, we should expect that any increase in the outside pressure would tend to prevent the solidification of substances which expand upon freezing. It ought therefore to require a lower temperature to freeze ice under a pressure of two atmospheres than under a pressure of one. Careful experiments have verified this conclusion and have shown that the melting point of ice is lowered .0075° C. for an increase of one atmosphere in the outside pressure. Although this lowering is so small a quantity, its existence may be shown as follows:

Let two pieces of ice be pressed firmly together beneath the surface of a vessel full of warm water. When taken out they will be found to be frozen together, in spite of the fact that they have been immersed in a medium much warmer than the freezing point of water. The explanation is as follows:

At the points of contact the pressure reduces the freezing point of the ice below 0° C., and hence it melts and gives rise to a thin film of water the temperature of which is slightly below 0° C. When this pressure is released, the film of water at once freezes, for its temperature is below the freezing point corresponding to ordinary atmospheric pressure. The same phenomenon may be even more strikingly illustrated by the following experiment:

Let two weights of from 5 to 10 kg. be hung by a wire over a block of ice as in Fig. 171. In half an hour or less the wire will be found to have cut completely through the block, leaving the ice, however, as solid as at first. The explanation is as follows: Just below the wire the ice melts because of the pressure; as the wire sinks through the layer of water thus formed, the pressure on the water is relieved and it immediately freezes again above the wire.

Fig. 171. Regelation

Geologists believe that the continuous flow of glaciers is partly due to the fact that the ice melts at points where the pressures become large, and freezes again when these pressures are relieved. This process of melting under pressure and freezing again as soon as the pressure is relieved is known as *regelation.*

Substances which expand on solidifying have their melting points lowered by pressure, and those which contract on solidifying have their melting points raised by pressure.

QUESTIONS AND PROBLEMS

1. What is the meaning of the statement that the heat of fusion of mercury is 2.8?

2. Explain how the presence of ice keeps the interior of a refrigerator from becoming warm.

3. How many times as much heat is required to melt any piece of ice as to warm the resulting water 1° C.? 1° F.? How many B. T. U. are required to melt 1 lb. of ice? How many foot pounds of energy are required to do the work of melting 1 lb. of ice?

4. If the heat of fusion of ice were 40 instead of 80, how would this affect the quantity of ice that would have to be bought for the refrigerator during the summer?

5. Five pounds of ice melted in 1 hr. in an unopened refrigerator. How many B. T. U. came through the walls of the refrigerator in the hour?

6. Just what will occur if 1000 calories be applied to 20 g. of ice at 0° C.?

7. How many grams of ice must be put into 200 g. of water at 40° C. to lower the temperature 10° C.?

8. How many grams of ice must be put into 500 g. of water at 50° C. to lower the temperature to 10° C.?

9. Why will snow pack into a snowball if the snow is melting, but not if it is much below 0° C.?

Evaporation and the Properties of Vapors

202. Evaporation and temperature. If it is true that increase in temperature means increase in the mean velocity of molecular motion, then the number of molecules which chance in a given time to acquire the velocity necessary to carry them into the space above the liquid ought to increase as the temperature increases; that is, evaporation ought to take place more rapidly at high temperatures than at low. Common observation teaches that this is true. Damp clothes become dry under a hot flatiron but not under a cold one; the sidewalk dries more readily in the sun than in the shade; we put wet objects near a hot stove or radiator when we wish them to dry quickly.

203. Evaporation of solids, — sublimation. That the molecules of a solid substance are found in a vaporous condition above the surface of the solid, as well as above that of a liquid, is proved by the often-observed fact that ice and snow evaporate even though they are kept constantly below the freezing point. Thus, wet clothes dry in winter after freezing. An even better proof is the fact that the odor of camphor can be detected many feet away from the camphor

crystals. The evaporation of solids may be rendered visible by the following striking experiment:

Let a few crystals of iodine be placed on a watch glass and heated gently with a Bunsen flame. The visible vapor of iodine will appear above the crystals, though none of the liquid is formed.

A great many substances at high temperatures pass from the solid to the gaseous condition without passing through the liquid state. *The vaporization of a solid is called sublimation.*

204. Saturated vapor. If a liquid is placed in an open vessel, there ought to be no limit to the number of molecules which can be lost by evaporation, for as fast as the molecules emerge from the liquid they are carried away by air currents. As a matter of fact, experience teaches that water left in an open dish does waste away until the dish is completely dry.

But suppose that the liquid is evaporating into a closed space, such as that shown in Fig. 172. Since the molecules which leave the liquid cannot escape from the space *S*, it is clear that as time goes on the number of molecules which have passed off from the liquid into this space must continually increase; in other words, the density of the vapor in *S* must grow greater and greater. But there is an absolutely definite limit to the density which the vapor can attain; for as soon as it reaches a certain value, depending on the temperature and on the nature of the liquid, the number of molecules returning per second to the liquid surface will be exactly equal to the number escaping. The vapor is then said to be *saturated.*

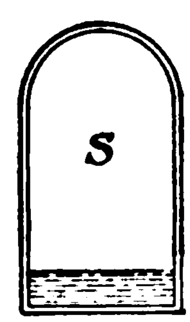


FIG. 172. A saturated vapor

If the density of the vapor is lessened temporarily by increasing the size of the vessel *S*, more molecules will escape from the liquid per second than return to it, until the density of the vapor has regained its original value.

If, on the other hand, the density of the vapor has been increased by compressing it, more molecules return to the liquid per second than escape, and the density of the vapor falls quickly to its saturated value. We learn, then, that *the density of the saturated vapor of a liquid depends on the temperature alone and cannot be affected by changes in volume.*

205. Pressure of a saturated vapor. Just as a gas exerts a pressure against the walls of the containing vessel by the blows of its moving molecules, so also does a confined vapor. But at any given temperature the density of a saturated vapor can have only a definite value; that is, there can be only a definite number of molecules per cubic centimeter. It follows, therefore, that just as at any temperature the saturated vapor can have only one density, so also it can have only one pressure. This pressure is called *the pressure of the saturated vapor* corresponding to the given temperature.

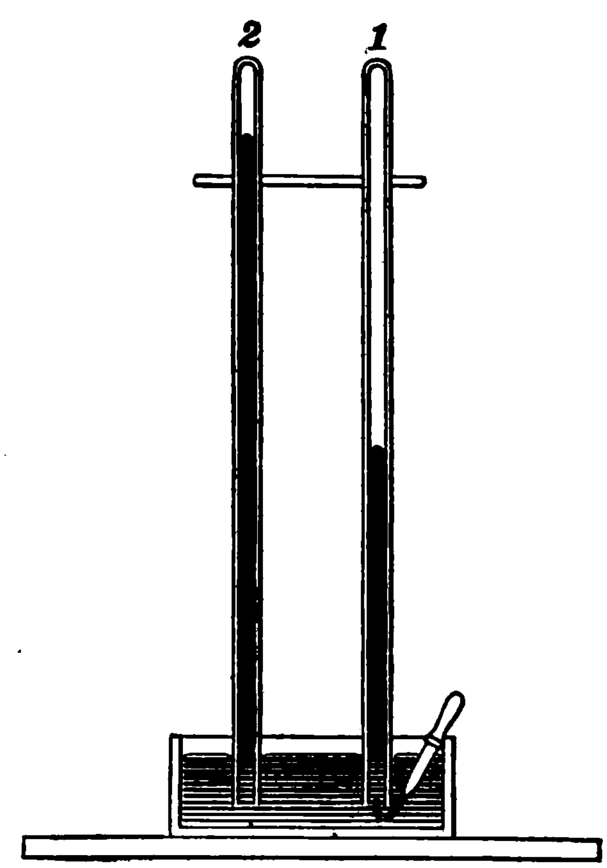


FIG. 173. Vapor pressure of a saturated vapor

Let two Torricelli tubes be set up as in Fig. 173, and with the aid of a curved pipette (Fig. 173) let a drop of ether be introduced into the bottom of tube 1. This drop will at once rise to the top, and a portion of it will evaporate into the vacuum which exists above the mercury. The pressure of this vapor will push down the mercury column, and the number of centimeters of this depression will of course be a measure of the pressure of the vapor. It will be observed that the mercury will fall almost instantly to the lowest level which it will ever reach,— a fact which indicates that it takes but a very short time for the condition of saturation to be attained.

The pressure of the saturated ether vapor at the temperature of the room will be found to be as much as 40 centimeters.

Let a Bunsen flame be passed quickly across the tubes of Fig. 173 near the upper level of the mercury. The vapor pressure will increase rapidly in tube 1, as shown by the fall of the mercury column.

The experiment proves that both the pressure and the density of a saturated vapor increase rapidly with the temperature. This was to have been expected from our theory, for increasing the temperature of the liquid increases the mean velocity of its molecules and hence increases the number which attain each second the velocity necessary for escape. How rapidly the density and pressure of saturated water vapor increase with temperature may be seen from the following table:

TABLE OF CONSTANTS OF SATURATED WATER VAPOR

The table shows the pressure P, in millimeters of mercury, and the density D of aqueous vapor saturated at temperatures t° C.

t.	P.	D.	t.	P.	D.	t.	P.	D.
– 10°	2.2	.0000023	4°	6.1	.0000064	18°	15.3	.0000152
– 9°	2.3	.0000025	5°	6.5	.0000068	19°	16.3	.0000162
– 8°	2.5	.0000027	6°	7.0	.0000073	20°	17.4	.0000172
– 7°	2.7	.0000029	7°	7.5	.0000077	21°	18.5	.0000182
– 6°	2.9	.0000032	8°	8.0	.0000082	22°	19.6	.0000193
– 5°	3.2	.0000034	9°	8.5	.0000087	23°	20.9	.0000204
– 4°	3.4	.0000037	10°	9.1	.0000093	24°	22.2	.0000216
– 3°	3.7	.0000040	11°	9.8	.0000100	25°	23.5	.0000229
– 2°	3.9	.0000042	12°	10.4	.0000106	26°	25.0	.0000242
– 1°	4.2	.0000045	13°	11.1	.0000112	27°	26.5	.0000256
0°	4.6	.0000049	14°	11.9	.0000120	28°	28.1	.0000270
1°	4.9	.0000052	15°	12.7	.0000128	30°	31.5	.0000301
2°	5.3	.0000056	16°	13.5	.0000135	35°	41.8	.0000393
3°	5.7	.0000060	17°	14.4	.0000144	40°	54.9	.0000509

206. The influence of air on evaporation. We observed that when ether was inserted into a Torricelli tube the mercury fell *very suddenly* to its final position, showing that in a vacuum the condition of saturation is reached almost instantly.

This was to have been expected from the great velocities which we found the molecules of gases and vapors to possess.

Let air be introduced into tube 2 (Fig. 173) until the mercury column stands at a height of from 45 to 55 cm. Measure the height of the mercury column. In order to see what effect the presence of air has upon evaporation, let a drop of ether be introduced into the tube. The mercury will not be found to sink instantly to its final level as it did before; but although it will fall rapidly at first, it will continue to fall slowly for several hours. At the end of a day, if the temperature has remained constant, it will show a depression which indicates a vapor pressure of the ether just as great as that existing in a tube which contains no air.

The experiment leads, then, to the rather remarkable conclusion that *just as much liquid will evaporate into a space which is already full of air as into a vacuum.* The air has no effect except to retard greatly the *rate of evaporation.*

207. Explanation of the retarding influence of air on evaporation. This retarding influence of air on evaporation is easily explained by the kinetic theory; for while in a vacuum the molecules which emerge from the surface fly at once to the top of the vessel, when air is present the escaping molecules collide with the air molecules before they have gone any appreciable distance away from the surface (probably less than .00001 centimeter), and only work their way up to the top after an almost infinite number of collisions. Thus, while the space immediately above the liquid may become saturated very quickly, it requires a long time for this condition of saturation to reach the top of the vessel.

QUESTIONS AND PROBLEMS

1. Account for the evaporation of naphthaline moth balls at ordinary room temperatures.

2. Why do clothes dry more quickly on a windy day than on a quiet day?

3. If the inside of a barometer tube is wet when it is filled with mercury, will the height of the mercury be the same as in a dry tube?

4. How many grams of water will evaporate at 20° C. into a closed room 18 × 20 × 4 m.? (See table, p. 171.)

5. At a temperature of 15° C. what will be the error in the barometric height indicated by a barometer which contains moisture?

6. At 20° C. how great was the error in reading due to the presence of water vapor in Otto von Guericke's barometer?

HYGROMETRY, OR THE STUDY OF MOISTURE CONDITIONS IN THE ATMOSPHERE *

208. Condensation of water vapor from the air. Were it not for the retarding influence of air upon evaporation we should be obliged to live in an atmosphere which would be always completely saturated with water vapor, for the evaporation from oceans, lakes, and rivers would almost instantly saturate all the regions of the earth. This condition — one in which moist clothes would never dry, and in which all objects would be perpetually soaked in moisture — would be exceedingly uncomfortable if not altogether unendurable.

But on account of the slowness with which, as the last experiment showed, evaporation into air takes place, the water vapor which always exists in the atmosphere is usually far from saturated, even in the immediate neighborhood of lakes and rivers. Since, however, the amount of vapor which is necessary to produce saturation rapidly decreases with a fall in temperature, if the temperature decreases continually in some unsaturated locality it is clear that a point must soon be reached at which the amount of vapor already existing in a cubic centimeter of the atmosphere is the amount corresponding to saturation. Then, if the temperature still continues to fall, the vapor must begin to condense. Whether it condenses as dew or cloud or fog or rain will depend upon how and where the cooling takes place.

* It is recommended that this subject be preceded by a laboratory determination of dew point, humidity, etc. See, for example, Experiment 10 of the authors' Manual.

209. The formation of dew and frost. If the cooling is due to the natural radiation of heat from the earth at night after the sun's warmth is withdrawn, the atmosphere itself does not fall in temperature nearly as rapidly as do solid objects on the earth, such as blades of grass, trees, stones, etc. The layers of air which come into immediate contact with these cooled bodies are themselves cooled, and as they thus reach a temperature at which the amount of moisture which they already contain is in a saturated condition, they begin to deposit this moisture, in the form of dew or frost, upon the cold objects. The drops of moisture which collect on an ice pitcher in summer illustrate perfectly the formation of dew. If condensation takes place upon a surface colder than the freezing temperature, *frost* is formed, as is observed, for instance, on grass and on windowpanes.

210. The formation of fog. If the cooling at night is so great as not only to bring the grass and trees below the temperature at which the vapor in the air in contact with them is in a state of saturation, but also to lower the whole body of air near the earth below this temperature, then the condensation takes place not only on the solid objects but also on dust particles suspended in the atmosphere. This constitutes a fog.

211. The formation of clouds, rain, sleet, hail, and snow. When the cooling of the atmosphere takes place at some distance *above* the earth's surface, as when a warm current of air enters a cold region, if the resultant temperature is below that at which the amount of moisture already in the air is sufficient to produce saturation, this excessive moisture immediately condenses about floating dust particles and forms a *cloud.* If the cooling is sufficient to free a considerable amount of moisture, the drops become large and fall as *rain.* If this falling rain freezes before it reaches the ground, it is called *sleet.* If the temperature at which condensation begins is below freezing, the condensing moisture forms into *snowflakes.*

When the violent air currents which accompany thunderstorms carry the condensed moisture up and down several times through alternate regions of snow and rain, *hailstones* are formed.

212. The dew point. *The temperature to which the atmosphere must be cooled in order that condensation of the water vapor within it may begin is called the dew point.* This temperature may be found by partly filling with water a brightly polished vessel of 200 or 300 cubic centimeters capacity and dropping into it little pieces of ice, stirring thoroughly at the same time with a thermometer. The dew point is the temperature indicated by the thermometer at the instant a film of moisture appears upon the polished surface. In winter the dew point is usually below freezing, and it will therefore be necessary to add salt to the ice and water in order to make the film appear. The experiment may be performed equally well by bubbling a current of air through ether contained in a polished tube (Fig. 174).

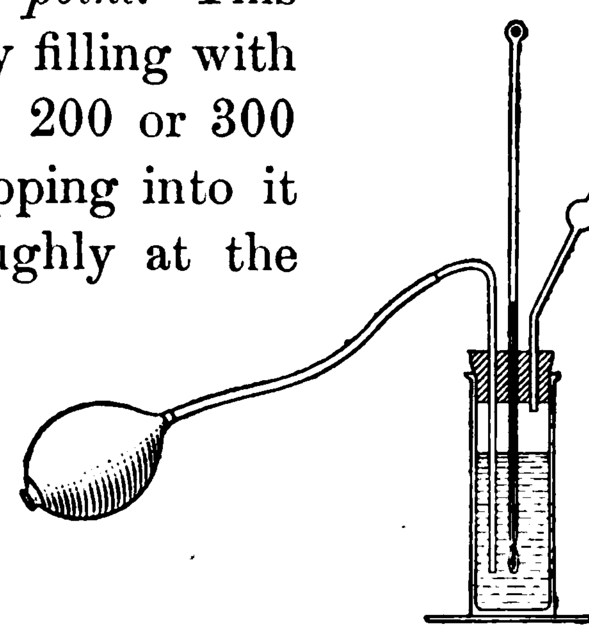


FIG. 174. Apparatus for determining dew point

213. Humidity of the atmosphere. From the dew point and table given in § 205, p. 171, we can easily find what is commonly known as the *relative humidity* or the *degree of saturation* of the atmosphere. *Relative humidity is defined as the ratio between the amount of moisture per cubic centimeter actually present in the air and the amount which would be present if the air were completely saturated.* This is precisely the same as the ratio between the pressure which the water vapor present in the air exerts and the pressure which it would exert if it were present in sufficient quantity to be in the saturated condition. An example will make clear the method of finding the relative humidity.

Suppose that the dew point were found to be 15° C. on a day on which the temperature of the room was 25° C. The amount of moisture actually present in the air then saturates it at 15° C. We see from the P column in the table that the pressure of saturated vapor at 15° C. is 12.7 millimeters. This is, then, the pressure exerted by the vapor in the air at the time of our experiment. Running down the table, we see that the amount of moisture required to produce saturation at the temperature of the room, that is, at 25°, would exert a pressure of 23.5 millimeters. Hence at the time of the experiment the air contains 12.7/23.5, or .54, as much water vapor as it might hold. We say, therefore, that the air is 54% saturated, or that the relative humidity is 54%.

214. Practical value of humidity determinations. From humidity determinations it is possible to obtain much information regarding the likelihood of rain or frost. Such observations are continually made for this purpose at all meteorological stations. They are also made in greenhouses, to see that the air does not become too dry for the welfare of the plants, and in hospitals and public buildings and even in private dwellings, in order to insure the maintenance of hygienic living conditions. For the most healthful conditions the relative humidity should be kept at from 50% to 60%.

Low relative humidity in the home causes discomfort and colds, and leads to waste of fuel estimated at from 10% to 25%. The average home heated to 72° F. by steam or hot water is estimated by health authorities to have a relative humidity of 30%, and even as little as 25% with hot-air heating. This is less than the average humidity of extensive desert regions. Higher humidity in the home would diminish the cooling effect due to rapid evaporation of the perspiration from the body, and would make us feel comfortable if a lower temperature were maintained (see § 215).

215. Cooling effect of evaporation. Let three shallow dishes be partly filled, the first with water, the second with alcohol, and the third with ether, the bottles from which these liquids are obtained having stood in the room long enough to acquire its temperature. Let three students

carefully read as many thermometers, first before their bulbs have been immersed in the respective liquids and then after. In every case the temperature of the liquid in the shallow vessel will be found to be somewhat lower than the temperature of the air, the difference being greatest in the case of ether and least in the case of water.

It appears from this experiment that an evaporating liquid assumes a temperature somewhat lower than its surroundings, and that the substances which evaporate the most readily assume the lowest temperatures.

In dry, hot climates where ice is not readily obtained drinking water is frequently kept in canvas bags or unglazed earthenware. The slow evaporation of the water from the outside of the porous container keeps the water within quite cool.

Another way of establishing the same truth is to place a few drops of each of the above liquids in succession on the bulb of the arrangement shown in Fig. 143 and observe the rise of water in the stem; or, more simply still, to place a few drops of each liquid on the back of the hand and notice that the order in which they evaporate — namely, ether, alcohol, water — is the order of greatest cooling.

In twenty-four hours a healthy person perspires from a pint to a quart, while one who exercises violently may perspire a gallon in that time.

216. Explanation of the cooling effect of evaporation. The kinetic theory furnishes a simple explanation of the cooling effect of evaporation. We saw that, in accordance with this theory, evaporation means an escape from the surface of those molecules which have acquired velocities considerably above the average. But such a continual loss of the most rapidly moving molecules involves, of course, a continual diminution of the average velocity of the molecules left behind, and this means a decrease in the temperature of the liquid.

Again, we should expect the amount of cooling to be proportional to the rate at which the liquid is losing molecules. Hence, of the three liquids studied, ether should cool most rapidly, since it evaporates most rapidly.

217. Freezing by evaporation. In § 206 it was shown that a liquid will evaporate much more quickly into a vacuum than into a space containing air. Hence, if we place a liquid under the receiver of an air pump and exhaust rapidly, we ought to expect a much greater fall in temperature than when the liquid evaporates into air. This conclusion may be strikingly verified as follows:

Let a thin watch glass be filled with ether and placed upon a drop of cold water, preferably ice water, which rests upon a thin glass plate. Let the whole arrangement be placed underneath the receiver of an air pump and the air rapidly exhausted. After a few minutes of pumping the watch glass will be found frozen to the plate.

By evaporating liquid helium in this way Professor Kamerlingh Onnes of Leyden, in 1911, attained the lowest temperature that had ever been reached, namely, $-271.3°$ C. ($-456.3°$ F.), less than 2° C. above absolute zero.

218. Effect of air currents upon evaporation. Let four thermometer bulbs, the first of which is dry, the second wetted with water, the third with alcohol, and the fourth with ether, be rapidly fanned and their respective temperatures observed. The results will show that in all of the wetted thermometers the fanning will considerably augment the cooling, but the dry thermometer will be wholly unaffected.

The reason why fanning thus facilitates evaporation, and therefore cooling, is that it removes the saturated layers of vapor which are in immediate contact with the liquid and replaces them by unsaturated layers into which new evaporation may at once take place. From the behavior of the dry-bulb thermometer, however, it will be seen that fanning produces cooling only when it can thus hasten evaporation. A dry body at the temperature of the room is not cooled in the slightest degree by blowing a current of air across it.

219. The wet- and dry-bulb hygrometer. In the wet- and dry-bulb hygrometer (Fig. 175) the principle of cooling by evaporation finds a very useful application. This instrument

consists of two thermometers, the bulb of one of which is dry, while that of the other is kept continually moist by a wick dipping into a vessel of water. Unless the air is saturated the wet bulb indicates a lower temperature than the dry one, for the reason that evaporation is continually taking place from its surface. How much lower will depend on how rapidly the evaporation proceeds, and this in turn will depend upon the relative humidity of the atmosphere. Thus, in a completely saturated atmosphere no evaporation whatever takes place at the wet bulb, and it consequently indicates the same temperature as the dry one. By comparing the indications of this instrument with those of the dew-point hygrometer (Fig. 174) tables have been constructed which enable one to determine at once from the readings of the two thermometers both the relative humidity and the dew point. On account of their convenience instruments of this sort are used almost exclusively in practical work. They are not very reliable unless the air is made to circulate about the wet bulb before the reading is taken. In scientific work this is always done.

FIG. 175. Wet- and dry-bulb hygrometer

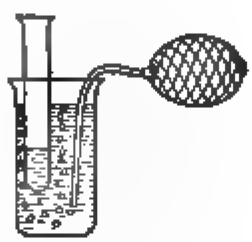


FIG. 176. Freezing water by the evaporation of ether

220. Effect of increased surface upon evaporation. Let a small test tube containing a few drops of water be dipped into a larger tube or a small glass containing ether, as in Fig. 176, and let a current of air be forced rapidly through the ether with an aspirator in the manner shown. The water within the tube will be frozen in a few minutes, if the aspirator is operated vigorously. The experiment works most successfully if the walls of the test tube are quite thin and the walls of the outer vessel fairly thick. Why?

The effect of passing bubbles through the ether is simply to increase enormously the evaporating surface, for the ether molecules which could before escape only at the upper surface can now escape into the air bubbles as well.

221. Factors affecting evaporation. The above results may be summarized as follows: The rate of evaporation depends (1) on the nature of the evaporating liquid; (2) on the temperature of the evaporating liquid; (3) on the degree of saturation of the space into which the evaporation takes place; √ (4) on the density of the air or other gas above the evaporating surface; (5) on the rapidity of the circulation of the air above the evaporating surface; (6) on the extent of the exposed surface of the liquid.

QUESTIONS AND PROBLEMS

1. Why do spectacle lenses become coated with mist on entering a warm house on a cold winter day?

2. Does dew "fall"?

3. Why are icebergs frequently surrounded with fog?

4. Dew will not usually collect on a pitcher of ice water standing in a warm room on a cold winter day. Explain.

5. The dew point in a room was found to be 8° C. What was the relative humidity if the temperature of the air was 10° C.? 20° C.? 30° C.? (Consult table, p. 171.)

6. What weight of water is contained in a room $5 \times 5 \times 3$ m. if the relative humidity is 60% and the temperature 20° C.? (See table, p. 171.)

7. If a glass beaker and a porous earthenware vessel are filled with equal amounts of water at the same temperature, in the course of a few minutes a noticeable difference of temperature will exist between the two vessels. Which will be the cooler, and why? Will the difference in temperature between the two vessels be greater in a dry or in a moist atmosphere?

8. Why will an open, narrow-necked bottle containing ether not show as low a temperature as an open shallow dish containing the same amount of ether?

9. Why is the heat so oppressive on a very damp day in summer?

10. A morning fog generally disappears before noon. Explain the reason for its disappearance.

11. What becomes of the cloud which you see about a blowing locomotive whistle? Is it steam?

12. Explain why it is necessary in winter to add moisture to the air of our homes to maintain proper relative humidity, but not necessary in the summer.

13. What factors affecting evaporation are illustrated by the following: (1) a wet handkerchief dries faster if spread out, (2) clothes dry best on a windy day, (3) clothes do not dry rapidly on a cold day, (4) clothes dry slowly on humid days? Explain each fact.

BOILING *

222. Heat of vaporization defined. The experiments performed in Chapter IV, Molecular Motions, led us to the conclusion that, at the free surface of any liquid, molecules frequently acquire velocities sufficiently high to enable them to lift themselves beyond the range of attraction of the molecules of the liquid and to pass off as free gaseous molecules into the space above. They taught us, further, that since it is only such molecules as have unusually high velocities which are able thus to escape, the *average kinetic energy* of the molecules left behind is continually diminished by this loss from the liquid of the most rapidly moving molecules, and consequently the temperature of an evaporating liquid constantly falls until the rate at which it is losing heat is equal to the rate at which it receives heat from outside sources. Evaporation, therefore, always takes place at the expense of the heat energy of the liquid. *The number of calories of heat which disappear in the formation of one gram of vapor is called the heat of vaporization of the liquid.*

223. Heat due to condensation. When molecules pass off from the surface of a liquid, they rise against the downward

* It is recommended that this subject be accompanied by a laboratory determination of the boiling point of alcohol by the direct method and by the vapor-pressure method, and that it be followed by an experiment upon the fixed points of a thermometer and the change of boiling point with pressure. See, for example, Experiments 23 and 24 of the authors' Manual.

forces exerted upon them by the liquid, and in so doing exchange a part of their kinetic energy for the potential energy of separated molecules in precisely the same way in which a ball thrown upward from the earth exchanges its kinetic energy in rising for the potential energy which is represented by the separation of the ball from the earth. Similarly, just as when the ball falls back it regains in the descent all of the kinetic energy lost in the ascent, so when the molecules of the vapor reënter the liquid they must regain all of the kinetic energy which they lost when they passed out of the liquid. We may expect, therefore, that *every gram of steam which condenses will generate in this process the same number of calories as was required to vaporize it.* This is the principle of the steam heating of buildings, by which the heat energy that disappears in converting the water in the boilers into steam is generated again when the steam condenses to water within the radiators.

224. Measurement of heat of vaporization. To find accurately the number of calories expended in the vaporization, or released in the condensation, of a gram of water at 100° C., we pass steam rapidly for two or three minutes from an arrangement like that shown in Fig. 177 into a vessel containing, say, 500 g. of water. We observe the initial and final temperatures and the initial and final weights of the water. If, for example, the gain in weight of the water is 16.5 g., we know that 16.5 g. of steam have been condensed. If the rise in temperature of the water is from 10° C. to 30° C., we know that $500 \times (30 - 10) = 10{,}000$ calories of heat have entered the water. If x represents the number of calories given up by 1 g. of steam in condensing, then the total heat imparted to the water by the condensation of the steam is $16.5\,x$ calories. This condensed steam is at first water at 100° C., which is then cooled to 30° C. In this cooling

FIG. 177. Heat of vaporization of water

process it gives up 16.5 × (100 − 30) = 1155 calories. Therefore, equating the heat gained by the water to the heat lost by the steam, we have

$$10{,}000 = 16.5\,x + 1155, \text{ or } x = 536.$$

This is the method usually employed for finding the heat of vaporization. The now accepted value of this constant is 536.

225. Boiling temperature defined. If a liquid is heated by means of a flame, it will be found that there is a certain temperature above which it cannot be raised, no matter how rapidly the heat is applied. This is the temperature which exists when bubbles of vapor form at the bottom of the vessel and rise to the surface, growing larger as they rise. This temperature is commonly called the *boiling temperature.*

But a second and more exact definition of the boiling point may be given. It is clear that a bubble of vapor can exist within the liquid only when the pressure exerted by the vapor within the bubble is at least equal to the atmospheric pressure pushing down on the surface of the liquid; for if the pressure within the bubble were less than the outside pressure, the bubble would immediately collapse. Therefore *the boiling point is the temperature at which the pressure of the saturated vapor first becomes equal to the pressure existing outside.*

226. Variation of the boiling point with pressure. Since the pressure of a saturated vapor varies rapidly with the temperature, and since the boiling point has been defined as the temperature at which the pressure of the saturated vapor is equal to the outside pressure, it follows that *the boiling point must vary as the outside pressure varies.*

Thus let a round-bottomed flask be half filled with water and boiled. After the boiling has continued for a few minutes, so that the steam has driven out most of the air from the flask, let a rubber stopper be inserted and the flask removed from the flame and inverted as shown in Fig. 178. The temperature will fall rapidly below the boiling point; but if cold water is poured over the flask, the water will again begin to boil vigorously, for the cold water, by condensing the steam, lowers the

pressure within the flask, and thus enables the water to boil at a temperature lower than 100° C. The boiling will cease, however, as soon as enough vapor is formed to restore the pressure. The operation may be repeated many times without reheating.

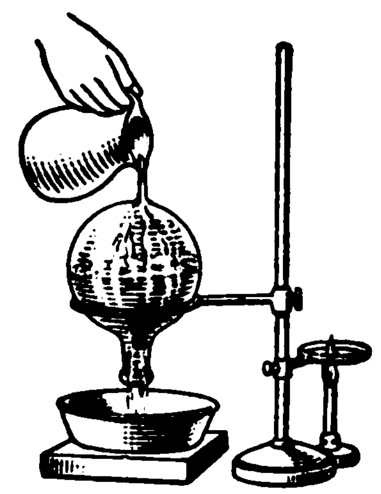


Fig. 178. Lowering the boiling point by diminishing the pressure

At the city of Quito, Ecuador, water boils at 90° C.; on the top of Mt. Blanc it boils at 84° C.; and on Pikes Peak, at 89° C. On the other hand, in the boiler of a locomotive on which the gauge records a pressure of 250 pounds, as is frequently the case, the boiling point of the water is 208° C. (406° F.).

Closed boilers provided with safety valves (see *C*, Fig. 179) and known as *digesters* are used for more rapid cooking in mountainous regions. Indeed, a temperature only a few degrees above 100° C. causes starch grains to burst open much more rapidly than does a temperature of 100° C. Large digesters are used in extracting gelatin from bones and in reclaiming valuable fatty substances at garbage plants. In the cold-pack method of preserving fruits and vegetables the final sterilizing is done by placing the jars or cans in closed boilers known as *steam-pressure canners.**

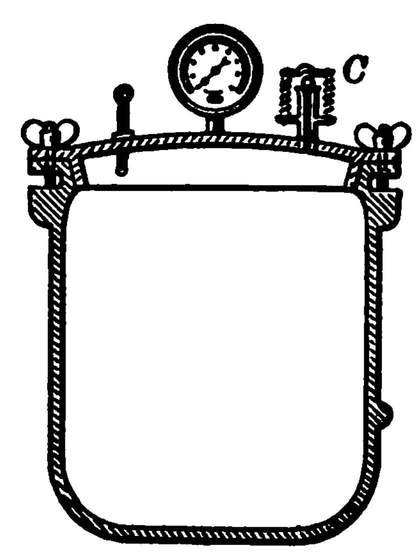


Fig. 179. A closed boiler for family use

227. Evaporation and boiling. The only essential difference between evaporation and boiling is that the former consists in the passage of molecules into the vaporous condition *from the free surface only*, while the latter consists in the passage of the molecules into the vaporous condition both at the free surface and at

* *Farmers' Bulletin No. 839*, on steam-pressure canning, may be obtained from the United States Department of Agriculture, Washington, D. C.

the surface of bubbles which exist within the body of the liquid. The only reason why vaporization takes place so much more rapidly at the boiling temperature than just below it is that the evaporating *surface* is enormously increased as soon as the bubbles form. The reason why the temperature cannot be raised above the boiling point is that the surface always increases, on account of the bubbles, to just such an extent that the loss of heat because of evaporation is exactly equal to the heat received from the fire.

228. Distillation. Let water holding in solution some aniline dye be boiled in B (Fig. 180). The vapor of the liquid will pass into the tube T, where it will be condensed by the cold water which is kept in continual circulation through the jacket J. The condensed water collected in P will be seen to be free from all traces of the color of the dissolved aniline.

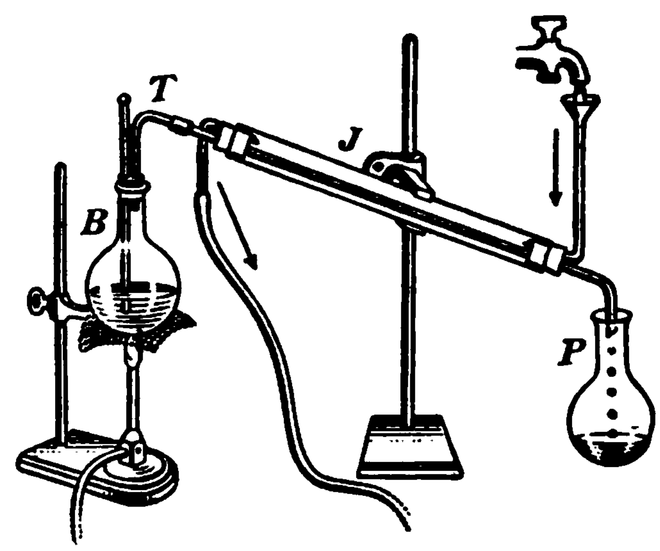


FIG. 180. Distillation

We learn, then, that *when solids are dissolved in liquids, the vapor which rises from the solution contains none of the dissolved substance.* Sometimes it is the pure liquid in P which is desired, as in the manufacture of alcohol, and sometimes the solid which remains in B, as in the manufacture of sugar. In the white-sugar industry it is necessary that the evaporation take place at a low temperature, so that the sugar may not be scorched. Hence the boiler is kept partially exhausted by means of an air pump, thus enabling the solution to boil at considerably reduced temperatures.

229. Fractional distillation. When both of the constituents of a solution are volatile, as in the case of a mixture of alcohol and water, the vapor of both will rise from the liquid. But the one which has the lower boiling point, that is, the higher

vapor pressure, will predominate. Hence, if we have in *B* (Fig. 180) a solution consisting of 50% alcohol and 50% water, it is clear that we can obtain in *P*, by evaporating and condensing, a solution containing a much larger percentage of alcohol. By repeating this operation a number of times we can increase the purity of the alcohol. This process is called *fractional distillation.* The boiling point of the mixture lies between the boiling points of alcohol and water, being higher the greater the percentage of water in the solution.

Gasoline and kerosene are separated from crude oil, and different grades of gasoline are separated from each other by fractional distillation.

QUESTIONS AND PROBLEMS

1. A fall of 1° C. in the boiling point is caused by rising 960 ft. How hot is boiling water at Denver, 5000 ft. above sea level?

2. How may we obtain pure drinking water from sea water?

3. After water has been brought to a boil, will eggs become hard any quicker when the flame is high than when it is low?

4. The hot water which leaves a steam radiator may be as hot as the steam which entered it. How, then, has the room been warmed?

5. In a vessel of water which is being heated fine bubbles rise long before the boiling point is reached. Why is this so? How can you distinguish between this phenomenon and boiling?

6. When water is boiled in a deep vessel, it will be noticed that the bubbles rapidly increase in size as they approach the surface. Give two reasons for this.

7. Why are burns caused by steam so much more severe than burns caused by hot water of the same temperature?

8. How many times as much heat is required to convert any body of boiling water into steam as to warm an equal weight of water 1° C.?

9. How many B. T. U. are liberated within a radiator when 10 lb. of steam condense there?

10. In a certain radiator 2 kg. of steam at 100° C. condensed to water in 1 hr. and the water left the radiator at 90° C. How many calories were given to the room during the hour?

11. How many calories are given up by 30 g. of steam at 100° C. in condensing and then cooling to 20° C.? How much water will this steam raise from 10° C. to 20° C.?

ARTIFICIAL COOLING

230. Cooling by solution. Let a handful of common salt be placed in a small beaker of water at the temperature of the room and stirred with a thermometer. The temperature will fall several degrees. If equal weights of ammonium nitrate and water at 15° C. are mixed, the temperature will fall as low as – 10° C. If the water is nearly at 0° C. when the ammonium nitrate is added, and if the stirring is done with a test tube partly filled with ice-cold water, the water in the tube will be frozen.

These experiments show that the breaking up of the crystals of a solid requires an expenditure of heat energy, as well when this operation is effected by solution as by fusion. The reason for this will appear at once if we consider the analogy between solution and evaporation; for just as the molecules of a liquid tend to escape from its surface into the air, so the molecules at the surface of the salt are tending, because of their velocities, to pass off, and are only held back by the attractions of the other molecules in the crystal to which they belong. If, however, the salt is placed in water, the attraction of the water molecules for the salt molecules aids the natural velocities of the latter to carry them beyond the attraction of their fellows. As the molecules escape from the salt crystals two forces are acting on them, the attraction of the water molecules tending to increase their velocities, and the attraction of the remaining salt molecules tending to diminish these velocities. If the latter force has a greater resultant effect than the former, the mean velocity of the molecules after they have escaped will be diminished and the solution will be cooled. But if the attraction of the water molecules amounts to more than the backward pull of the dissolving molecules, as when caustic potash or sulphuric acid is dissolved, the mean molecular velocity is increased and the solution is heated.

231. Freezing points of solutions. If a solution of one part of common salt to ten of water is placed in a test tube and immersed in a "freezing mixture" of water, ice, and salt, the

temperature indicated by a thermometer in the tube will not be zero when ice begins to form, but several degrees below zero. *The ice which does form, however, will be found, like the vapor which rises above a salt solution, to be free from salt*, and it is this fact which furnishes a key to the explanation of why the freezing point of the salt solution is lower than that of pure water. For cooling a substance to its freezing point simply means reducing its temperature, and therefore the mean velocity of its molecules, sufficiently to enable the cohesive forces of the liquid to pull the molecules together into the crystalline form. Since in the freezing of a salt solution the cohesive forces of the water are obliged to overcome the attractions of the salt molecules as well as the molecular motions, the motions must be rendered less, that is, the temperature must be made lower, than in the case of pure water in order that crystallization may occur. From this reasoning we should expect that the larger the amount of salt in solution the lower would be the freezing point. This is indeed the case. The lowest freezing point obtainable with common salt in water is $-22°$ C., or $-7.6°$ F. This is the freezing point of a saturated solution.

232. Freezing mixtures. If snow or ice is placed in a vessel of water, the water melts it, and in so doing its temperature is reduced to the freezing point of pure water. Similarly, if ice is placed in salt water, it melts and reduces the temperature of the salt water to the freezing point of the solution. This may be one, or two, or twenty-two degrees below zero, according to the concentration of the solution. Therefore, whether we put the ice in pure water or in salt water, enough of it always melts to reduce the whole mass to the freezing point of the liquid, and each gram of ice which melts uses up 80 calories of heat. *The efficiency of a mixture of salt and ice in producing cold is therefore due simply to the fact that the freezing point of a salt solution is lower than that of pure water.*

The best proportions are three parts of snow or finely shaved ice to one part of common salt. If three parts of calcium chloride are mixed with two parts of snow, a temperature of $-55°$ C. may be produced. This is low enough to freeze mercury.

QUESTIONS AND PROBLEMS

1. When salt water freezes, the ice formed is free from salt. What effect, then, does freezing have on the concentration of a salt solution?

2. A partially concentrated salt solution which has a freezing point of $-5°$ C. is placed in a room which is kept at $-10°$ C. Will it all freeze?

3. Explain why salt is thrown on icy sidewalks on cold winter days.

4. Give two reasons why the ocean freezes less easily than the lakes.

5. Why does pouring H_2SO_4 into water produce heat, while pouring the same substance upon ice produces cold?

6. Why will a liquid which is unable to dissolve a solid at a low temperature often do so at a higher temperature? (See § 230.)

7. When the salt in an ice-cream freezer unites with the ice to form brine, about how many calories of heat are used for each gram of ice melted? Where does it come from? If the freezing point of the salt solution were the same as that of the cream, would the cream freeze?

INDUSTRIAL APPLICATIONS

233. The modern steam engine. Thus far in our study of the transformations of energy we have considered only cases in which mechanical energy was transformed into heat energy. In all heat engines we have examples of exactly the reverse operation, namely, the transformation of heat energy back into mechanical energy. How this is done may best be understood from a study of various modern forms of heat engines. The invention of the form of the steam engine which is now in use is due to James Watt, who, at the time of the invention (1768), was an instrument maker in the University of Glasgow.

The operation of such a machine can best be understood from the ideal diagram shown in Fig. 181. Steam generated in the boiler B by the fire F passes through the pipe S into

the steam chest *V*, and thence through the passage *N* into the cylinder *C*, where its pressure forces the piston *P* to the left. It will be seen from the figure that as the driving rod *R* moves toward the left the so-called eccentric rod *R′*, which controls the valve *V*, moves toward the right. Hence, when the piston has reached the left end of its stroke, the passage

FIG. 181. Ideal diagram of a steam engine

N will have been closed, while the passage *M* will have been opened, thus throwing the pressure from the right to the left side of the piston, and at the same time putting the right end of the cylinder, which is full of spent steam, into connection with the exhaust pipe *E*. This operation goes on continually, the rod *R′* opening and closing the passages *M* and *N* at just the proper moments to keep the piston moving back and forth throughout the length of the cylinder. The shaft carries a heavy flywheel *W*, the great inertia of which insures constancy in speed. The motion of the shaft is communicated to any

A TANK

The land battleships called tanks were invented to combat the deadly machine guns. They rolled along on two endless steel belts running lengthwise of the machine. Some of the tanks were armed with 3-inch guns and could travel over the roughest ground, down into great shell holes and out again, over trenches, and through masses of barbed wire, and could even break down and run over trees a foot in diameter, as shown in the picture. The smaller tanks were armed with machine guns and could travel as fast as the enemy infantry could run

THE LIBERTY MOTOR

This 400-horse-power motor, one of America's important contributions to the World War, was developed for use on the larger types of bombing airplanes. It makes 1700 revolutions per minute and has twelve cylinders, which are water-cooled. It weighs 806 pounds, or about 2 pounds per horse power. The *NC*-4, which made the first transatlantic flight, was equipped with three of these motors

desired machinery by means of a belt which passes over the pulley W'. Within the boiler the steam is at high pressure and high temperature (§ 226). The steam falls in temperature within the cylinder while doing the work of pushing the piston. *A steam engine is a mechanical device which accomplishes useful work by transforming heat energy into mechanical energy.*

234. Condensing and noncondensing engines. In most stationary engines the exhaust E leads to a condenser which consists of a chamber Q, into which plays a jet of cold water T, and in which a partial vacuum is maintained by means of an air pump. In the best engines the pressure within Q is not more than from 3 to 5 centimeters of mercury, that is, not more than a pound to the square inch. Hence the condenser reduces the back pressure against that end of the piston which is open to the atmosphere from 15 pounds down to 1 pound, and thus increases the effective pressure which the steam on the other side of the piston can exert.

235. The eccentric. In practice the valve rod R' is not attached as in the ideal engine indicated in Fig. 181, but motion is communicated to it by a so-called *eccentric*. This consists of a circular disk K (Fig. 182) rigidly attached to the axle but so set that its center does not coincide with the center of the axle A. The disk K rotates inside the collar C and thus communicates to the eccentric rod R' a back-and-forth motion which operates the valve V in such a way as to admit steam alternately through M and N at the proper time.

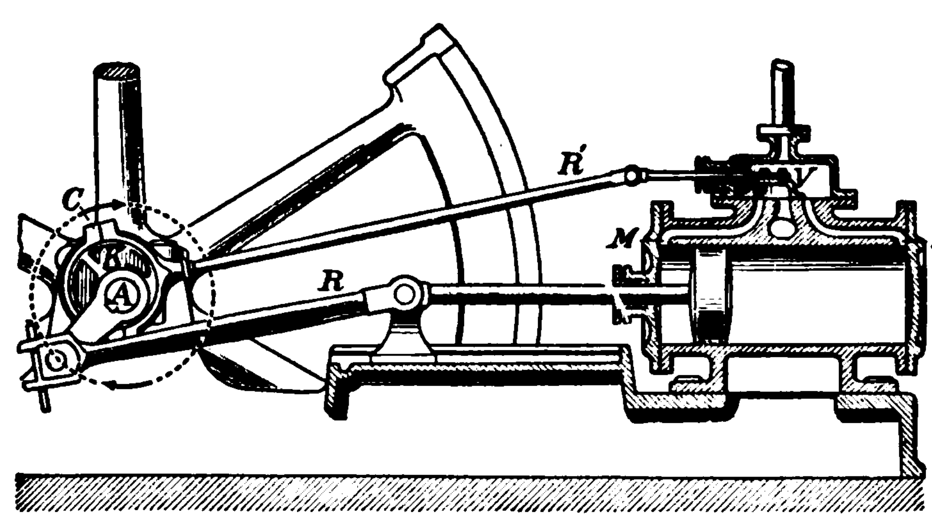


FIG. 182. The eccentric

236. The boiler. When an engine is at work, steam is being removed very rapidly from the boiler; for example, a railway locomotive consumes from 3 to 6 tons of water per hour. It is therefore necessary to have

the fire in contact with as large a surface as possible. In the tubular boiler this end is accomplished by causing the flames to pass through a large number of metal tubes immersed in water. The arrangement

FIG. 183. Diagram of locomotive

of the furnace and the boiler may be seen from the diagram of a locomotive shown in Fig. 183. (See early and modern types opposite p. 123.)

237. The draft. In order to force the flames through the tubes *B* of the boiler a powerful draft is required. In locomotives this is obtained by running the exhaust steam from the cylinder *C* (Fig. 183) into the smokestack *E* through the blower *F*. The strong current through *F* draws with it a portion of the air from the smoke box *D*, thus producing within *D* a partial vacuum into which a powerful draft rushes from the furnace through the tubes *B*. The coal consumption of an ordinary locomotive is from one-fourth ton to one ton per hour.

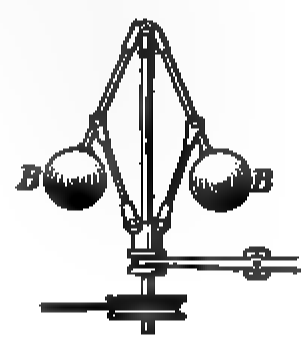


FIG. 184. The governor

In stationary engines a draft is obtained by making the smokestack very high. Since in this case the pressure which is forcing the air through the furnace is equal to the difference in the weights of columns of air of unit cross section inside and outside the chimney, it is evident that this pressure will be greater the greater the height of the smokestack. This is the reason for the immense heights given to chimneys in large power plants.

238. The governor. Fig. 184 shows an ingenious device of Watt's, called a *governor*, for automatically regulating the speed with which a stationary engine runs. If it runs too fast, the heavy rotating balls *B*

move apart and upward and in so doing operate a valve which reduces the speed by partially shutting off the supply of steam from the cylinder.

239. Compound engines. In an engine which has but a single cylinder the full force of the steam has not been spent when the cylinder is opened to the exhaust. The waste of energy which this entails is obviated in the compound engine (see Fig. 311) by allowing the partially spent steam to pass into a second cylinder of larger area than the first. The most efficient of modern engines have three and sometimes four cylinders of this sort, and the engines are accordingly called *triple* or *quadruple expansion engines.* Fig. 185 shows the relation between any two successive cylinders of a cross-compound engine. By automatic devices not differing in principle from the eccentric, valves C^1, D^2, and E^2 open simultaneously and thus permit steam from the boiler to enter the small cylinder A, while the partially spent steam in the other end of the same cylinder passes through D^2 into B, and the more fully exhausted steam in the upper end of B passes out through E^2. At the upper end of the stroke of the pistons P and P', C^1, D^2, and E^2 automatically close, while C^2, D^1, and E^1 simultaneously open and thus reverse the direction of motion of both pistons. These pistons are attached to the same shaft.

FIG. 185. Cross-compound engine cylinders

240. Efficiency of a steam engine. We have seen that it is possible to transform completely a given amount of mechanical energy into heat energy. This is done whenever a moving body is brought to rest by means of a frictional resistance. But the inverse operation, namely, that of transforming heat energy into mechanical energy, differs in this respect, that it is only a comparatively small fraction of the heat developed by combustion which can be transformed into work. For it is not difficult to see that in every steam engine at least a part of the heat must of necessity pass over with the exhaust steam into the condenser or out into the atmosphere. This loss is so

great that even in an ideal engine not more than about 23% of the heat of combustion could be transformed into work. In practice the very best condensing engines of the quadruple-expansion type transform into mechanical work not more than 17% of the heat of combustion. Ordinary locomotives utilize at most not more than 8%. *The efficiency of a heat engine is defined as the ratio between the heat utilized, or transformed into work, and the total heat expended.* The efficiency of the best steam engines is therefore about $\frac{17}{23}$, or 75%, of that of an ideal heat engine, while that of the ordinary locomotive is only about $\frac{6}{23}$, or 26%, of the ideal limit.

241. Principle of the internal-combustion engine. Let two iron or steel wires be pushed through a cork stopper and their ends *s* brought near together (1/32 inch will do) (Fig. 186). With an atomizer spray into the bottle a small amount of benzine or gasoline (the amount to use can be determined by trial), insert the stopper, and bring the tips of the heavily insulated wires leading from an induction coil to the underside of the wires *a*, *b*. A spark will pass at *s*; and, if the mixture is not too "rich" or too "lean," a violent explosion will occur, throwing the stopper as high as the ceiling. (*A heavy round bottle must be used for safety. Wrap it well in wire gauze.*)

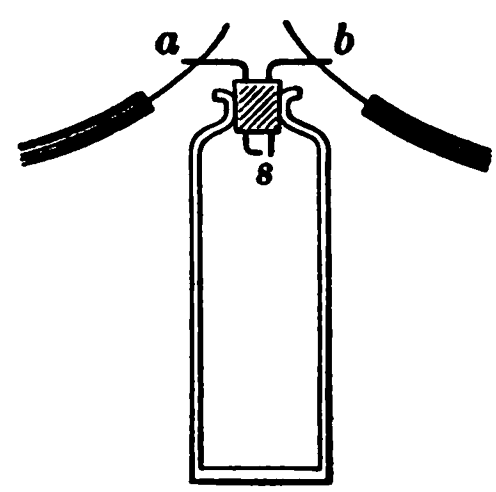


FIG. 186. A mixture of gasoline vapor and air will explode

Within the last two decades gas engines have become quite as important a factor in modern life as steam engines. (See opposite pp. 190, 191, and 198.) Such engines are driven by properly timed explosions of a mixture of gas and air occurring within the cylinder.

Fig. 187 is a diagram illustrating the four stages into which it is convenient to divide the complete cycle of operations which goes on within such an engine. Suppose that the heavy flywheel *W* has already been set in motion. As the piston *p* moves down in the first stroke (see *1*) the valve *D*

opens and an explosive mixture of gas and air is drawn into the cylinder through *D*. As the piston rises (see *2*) valve *D* closes, and the mixture of gas and air is compressed into a small space in the upper end of the cylinder. An electric spark ignites the explosive mixture, and the force of the explosion drives the piston violently down (see *3*). At the beginning of the return stroke (see *4*) the exhaust valve *E* opens, and as the piston moves up, the spent gaseous products of the explosion are forced out of the cylinder. The initial condition is thus restored and the cycle begins over again.

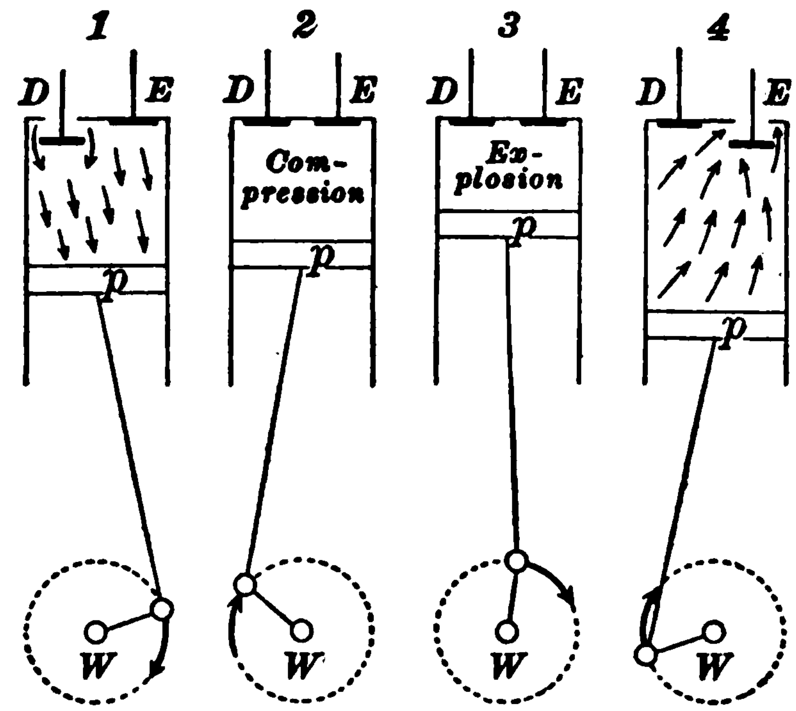


FIG. 187. Principle of the gas engine

Since it is only during the third stroke that the engine is receiving energy from the exploding gas, the flywheel is always made very heavy so that the energy stored up in it in the third stroke may keep the machine running with little loss of speed during the other three parts of the cycle.

The efficiency of the gas engine is often as high as 25%, or nearly double that of the best steam engines. Furthermore, it is free from smoke, is very compact, and may be started at a moment's notice. On the other hand, the fuel (gas or gasoline) is comparatively expensive. Most automobiles are run by gasoline engines, chiefly because the lightness of the engine and of the fuel to be carried are here considerations of great importance.

It has been the development of the light and efficient gas engine which has made possible man's recent conquest of the air through the use of the airplane and airship.

242. The automobile. The plate opposite page 198 shows the principal mechanical features of the automobile in their relation to one another. It will be seen that the cylinders

of the engine are surrounded by water jackets which form part of a circulating system. The heat of the engine is carried by convection currents in this water to the radiator, where it is lost to the atmosphere through the air currents produced in part by a revolving fan (10). Unless some means were provided for cooling a gas engine, it would become so overheated that the pistons would stick fast. The power of the engine is transmitted to the rear axle through the clutch (11), the transmission (12), and the differential gearing.

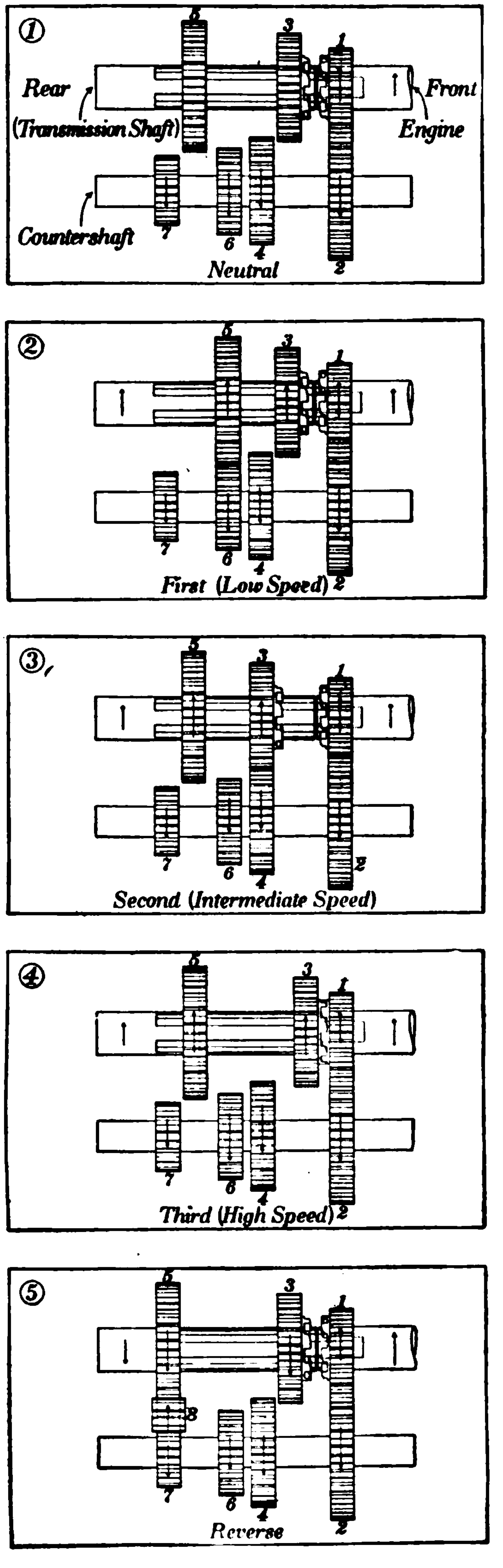


FIG. 188. Automobile transmission

243. The clutch and the transmission. Since a gas engine develops its power by a series of violent explosions within the cylinders, it is clear that it cannot start with a load as does the steam engine. In starting an automobile it is first necessary that the engine acquire a reasonable speed and that the power be applied gradually to the rear axle by the use of a friction clutch (11); otherwise the engine will stall. The shaft of the engine has upon its rear end a flywheel which, in the *cone* clutch, is turned to a conical shape inside. Close to this but attached to the transmission shaft is the clutch plate, a heavy disk faced with leather, which

fits the inside of the flywheel and is pressed into it by a spring sufficiently strong to prevent any slipping when the clutch is engaged. The driver throws out the clutch by depressing a lever with his foot. In the *disk* clutch the bearing surfaces are two series of disks, one revolving with the engine shaft, the other with the transmission.

The amount of work done by a gas engine in a minute depends upon the work done by each explosion multiplied by the number of explosions per minute. Therefore it can develop its full power only while revolving rapidly. In hill climbing, for example, the speed of the engine must be great while that of the car is comparatively small. To meet this requirement a system of reduction gears called the transmission (12) is used to make the number of revolutions of the driving shaft less than that of the crank shaft (4) of the engine. In Fig. 188, (*1*), the gears are in *neutral*, gears *1* and *2* being always in mesh. By use of the gear-shift lever (14) gears *3* and *5* (Fig. 188) are made to slide upon a square shaft. Before shifting the gears the clutch is released to disconnect the power of the motor from the driving shaft; and, to avoid a clash when meshing the gears on the transmission shaft with those on the countershaft, care should be taken that they revolve at about the same speed. Fig. 188, (*2*), shows the low-speed connection. In shifting to second speed (Fig. 188, (*3*)) the clutch is released, gear *5* is thrown into neutral, and finally gear *3* is meshed with *4*, after which the clutch is allowed to grip. In going to high speed (Fig. 188, (*4*)) gear *3* is shifted through neutral to engagement with gear *1*. This connects the crank shaft of the engine directly to the driving shaft so that the two revolve at the same speed. For the reverse (Fig. 188, (*5*)) an eighth gear is thrown up from beneath so as simultaneously to engage *5* and *7*. Such an interposition of a third gear wheel between *5* and *7* obviously reverses the direction of rotation of the driving shaft.

244. The differential. An automobile is driven by power applied to the rear axle. This requires the axle to be in two parts with a *differential* between, so that in turning corners the outer wheel may revolve faster than the inner. It will be seen from the large drawing opposite page 198, and from Fig. 189, that the pinion

Fig. 189. The differential

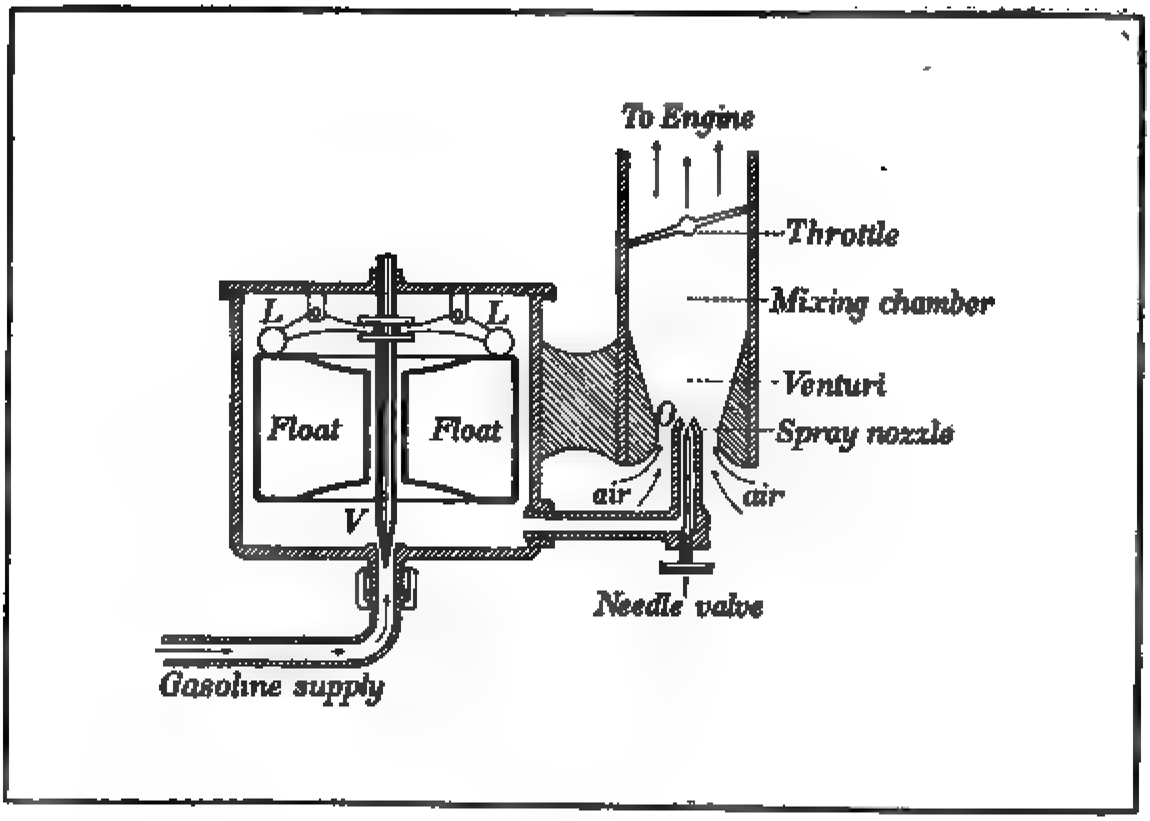
attached to the driving shaft rotates the main bevel gear *B*, to which are rigidly attached the differential gears *1* and *2*. The left axle is directly connected to gear *3*, and only indirectly connected to the main bevel gear *B* through gears *1* and *2*. In running straight both rear wheels revolve at the same rate; therefore, while gears *3* and *4* and the main bevel gear are revolving at the same speed they carry around with them pinions *1* and *2*, which are now, however, not revolving on their bearings. When the car is turning a corner, gears *3* and *4* are turning at *different* rates; hence pinions *1* and *2* are not only carried around by the main bevel gear but at the same time are revolved in opposite directions on their bearings.

245. The carburetor. The carburetor is a device for converting liquid gasoline, kerosene, etc. into vapor and mixing it with air in proper proportions for complete combustion. The simple principle of carburetion is shown in the upper diagram opposite page 199. Liquid gasoline comes through the supply pipe and enters the float chamber through the valve *V*. By acting on the levers *L* the float closes the valve *V* when the gasoline reaches a certain level. From the float chamber the gasoline is drawn to the spray nozzle *O*. While the engine is running, the downward movement of the pistons in stroke *1* (Fig. 187) sucks air violently past the spray nozzle into the region called the *venturi*, where the jet of gasoline is emerging from *O*. The spray of fuel thus formed intermingles with air in the mixing chamber and passes by the throttle to the engine as a highly explosive mixture.

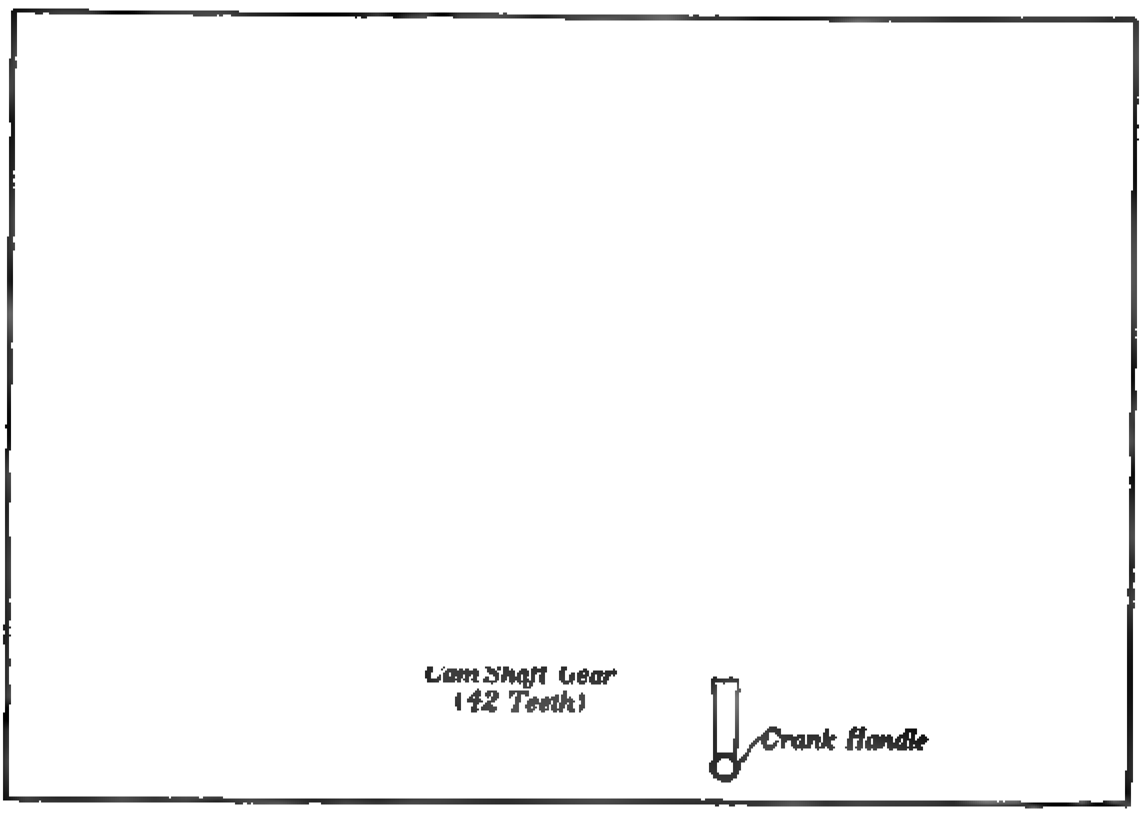
246. The ignition. The lower diagram opposite page 199 illustrates the principle of high-tension magneto ignition which is widely used on automobiles. A rolling contact *R* is mounted on the cam shaft, which revolves at half crank-shaft speed and is carried around the interior of the stationary fiber ring *D*. When the switch *S* is closed and the roller *R* passes across the metal segment *G*, a current of electricity passes from the magneto through the rolling contact to the central shaft *C*, and from there through the iron work of the car to the magneto by way of the primary coil of the induction coil. While the roller is in contact with the segment *G* the induction coil produces a shower of sparks between the points *P* of the spark plug, thus igniting the explosive mixture in the cylinder of the engine. Since the power stroke of the piston occurs but once in two revolutions of the crank shaft, it is necessary that the crank shaft revolve twice while the contact revolves but once. This, as shown in the diagram, is accomplished by having the crank shaft geared to the cam shaft in a velocity ratio of 2 to 1.

SECTION OF A MODERN AUTOMOBILE, SHOWING PRINCIPAL MECHANICAL PARTS

1, radiator; 2, timing gears; 3, pistons; 4, crank shaft; 5, valve stems and push rods; 6, oil reservoir; 7, gasoline tank; 8, flywheel; 9, main rear bearing; 10, cooling fan; 11, clutch; 12, transmission; 13, universal joints; 14, gear-shift lever; 15, main driving gear and pinion; 16, electric control switch; 17, emergency brake lever; 18, service brake foot lever; 19, storage battery; 20, vacuum feed system; 21, muffler; 22, steering wheel



The Carburetor



An Ignition System

The explosive mixture requires a very short but measurable time for combustion; hence the full force of the explosion occurs a short time *after* the spark ignites the mixture. Therefore, at high speed the spark should occur a little earlier with reference to the position of the piston than at low speed. The spark is *advanced* or *retarded* by a spark lever L which changes the position of the segment G by pulling around slightly the movable fiber ring to which it is attached.

The diagram applies to a one-cylinder engine. In case the engine has four cylinders, three additional segments must be added, as indicated by the clear spaces, together with three additional induction coils and spark plugs.*

247. The steam turbine. The steam turbine represents the latest development of the heat engine. In principle it is very much like the common windmill, the chief difference being that it is steam instead of air which is driven at a high velocity against a series of blades arranged radially about the circumference of the wheel that is set into rotation. The steam, however, unlike the wind, is always directed by nozzles at the angle of greatest efficiency against the blades (see Fig. 190). Furthermore, since the energy of the steam is far from spent after it has passed through one set of blades (such as that shown in Fig. 190), it is in practice always passed through a whole series of such sets (Fig. 191), every alternate row of which is rigidly attached to the rotating shaft, while the intermediate rows are fastened to the immovable outer jacket of the engine and only serve as guides to redirect the steam at the most favorable angle against the next row of movable blades. In this way the steam is kept alternately bounding from fixed to movable blades until its energy is expended. The number of rows of blades is often as high as sixteen.

Fig. 190. The principle of the steam turbine

* The pupil may well consult the more extended treatises for actual details of the many different systems of ignition used on automobile and airplane engines.

Turbines are at present coming rapidly into use, chiefly for large-power purposes. Their advantages over the reciprocating steam engine lie first in the fact that they run with almost no jarring, and therefore require much lighter and less expensive foundations, and second in the fact that they occupy less than one tenth the floor space of ordinary engines of the same capacity. Their efficiency is fully as high as that

Exhaust

Revolving

Stationary

Revolving

Nozzle

Fig. 191. Path of steam in Curtis's turbine

of the best reciprocating engines. The highest speeds attained by vessels at sea, namely, about 40 miles per hour, have been made with the aid of steam turbines. The largest vessel which has thus far ever been launched, the *Imperator*, 919 feet long, 98 feet wide, 100 feet high (from the keel to the top of her ninth deck), having a total displacement of 52,000 tons and a speed of $22\frac{1}{2}$ knots, is driven by four steam turbines having a total horse power of 72,000. One of the immense rotors contains 50,000 blades and develops 22,000 horse power. The United States Shipping Board, on July 24, 1919, announced plans for

building two gigantic ocean liners swifter and larger than any afloat. They are to be 1000 feet long and are to have a horse power of 110,000 and a speed of 30 knots. (See opposite p. 135.)

248. Manufactured ice. In the great majority of modern ice plants the low temperature required for the manufacture of the ice is produced by the rapid evaporation of liquid ammonia. At ordinary temperatures ammonia is a gas, but it may be liquefied by pressure alone. At 80° F. a pressure of 155 pounds per square inch, or about 10 atmospheres, is required to produce its liquefaction. Fig. 192 shows the essential parts of an ice plant. The compressor, which is usually run by a steam engine,

FIG. 192. Compression system of ice manufacture

forces the gaseous ammonia under a pressure of 155 pounds into the condenser coils shown on the right, and there liquefies it. The heat of condensation of the ammonia is carried off by the running water which constantly circulates about the condenser coils. From the condenser the liquid ammonia is allowed to pass very slowly through the regulating valve *V* into the coils of the evaporator, from which the evaporated ammonia is pumped out so rapidly that the pressure within the coils does not rise above 34 pounds. It will be noted from the figure that the same pump which is there labeled the compressor exhausts the ammonia from the evaporating coils and compresses it in the condensing coils, for the valves are so arranged that the pump acts as an exhaust pump on one side and as a compression pump on the other. The rapid evaporation of the liquid ammonia under the reduced pressure existing

within the evaporator cools these coils to a temperature of about 5° F. The brine with which these coils are surrounded has its temperature thus reduced to about 16° or 18° F. This brine is made to circulate about the cans containing the water to be frozen. The heat of vaporization of ammonia at 5° F. is 314 calories.

Many thousands of feet of circulating saltwater pipe are laid horizontally and covered with water to be frozen for large indoor skating rinks.

249. Cold storage. The artificial cooling of factories and cold-storage rooms is accomplished in a manner exactly similar to that employed in the manufacture of ice. The brine is cooled precisely as described above, and is then pumped through coils placed in the rooms to be cooled. In some systems carbon dioxide is used instead of ammonia, but the principle is in no way altered. Sometimes, too, the brine is dispensed with, and the air of the rooms to be cooled is forced by means of fans directly over the cold coils containing the evaporating ammonia or carbon dioxide. It is in this way that theaters and hotels are cooled.

QUESTIONS AND PROBLEMS

1. Why is a gas engine called an internal-combustion engine?

2. Why do gasoline engines have flywheels? Why is a one-cylinder engine of the four-cycle type especially in need of a flywheel?

3. How does the temperature of the steam within a locomotive boiler compare with its temperature at the moment of exhaust? Explain.

4. On the drive wheels of locomotives there is a mass of iron opposite the point of attachment of the drive shaft. Why is this necessary?

5. Why does not the water in a locomotive boil at 100° C.?

6. If liquid oxygen is placed in an open vessel, its temperature will not rise above −182° C. Why not? Suggest a way in which its temperature could be made to rise above −182° C., and a way in which it could be made to fall below that temperature.

7. How many foot pounds of energy are there in 1 lb. of coal containing 14,000 B.T.U. per pound? How many pounds of iron must be held at a height of 150 ft. to have as much energy as this pound of coal?

8. The average locomotive has an efficiency of about 6%. What horse power does it develop when it is consuming 1 ton of coal per hour? (See Problem 7, above.)

9. What amount of useful work did a gasoline engine working at an efficiency of 25% do in using 100 lb. of gasoline containing 18,000 B.T.U. per pound?

10. What pull does a 1000 H.P. locomotive exert when it is running at 25 mi. per hour and exerting its full horse power?

CHAPTER XI

THE TRANSFERENCE OF HEAT

Conduction

250. Conduction in solids. If one end of a short metal bar is held in the fire, the other end soon becomes too hot to hold; but if the metal rod is replaced by one of wood or glass, the end away from the flame is not appreciably heated.

This experiment and others like it show that nonmetallic substances possess much less ability to conduct heat than do metallic substances. But although all metals are good conductors as compared with nonmetals, they differ widely among themselves in their conducting powers.

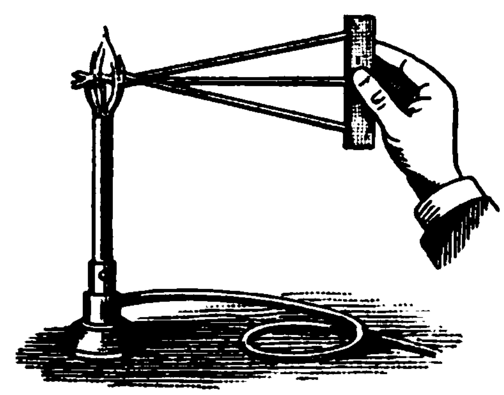


Fig. 193. Differences in the heat conductivities of metals

Let copper, iron, and German-silver wires 50 cm. long and about 3 mm. in diameter be twisted together at one end as in Fig. 193, and let a Bunsen flame be applied to the twisted ends. Let a match be slid slowly from the cool end of each wire toward the hot end, until the heat from the wire ignites it. The copper will be found to be the best conductor and the German silver the poorest.

In the following table some common substances are arranged in the order of their heat conductivities. The measurements have been made by a method not differing in principle from that just described. For convenience, silver is taken as 100.

Silver	100	Tin	15	Mercury . . .	1.5
Copper . . .	74	Iron	12	Ice	.21
Aluminium . .	48	Lead	8.5	Glass	.15
Brass	27	German silver .	6.3	Hard rubber .	.04

251. Conduction in liquids and gases. Let a small piece of ice be held by means of a glass rod in the bottom of a test tube full of ice water. Let the upper part of the tube be heated with a Bunsen burner as in Fig. 194. The upper part of the water may be boiled for some time without melting the ice. Water is evidently, then, a very poor conductor of heat. The same thing may be shown more strikingly as follows: The bulb of an air thermometer is placed only a few millimeters beneath the surface of water contained in a large funnel arranged as in Fig. 195. If now a spoonful of ether is poured on the water and set on fire, the index of the air thermometer will show scarcely any change, in spite of the fact that the air thermometer is a very sensitive indicator of changes in temperature.

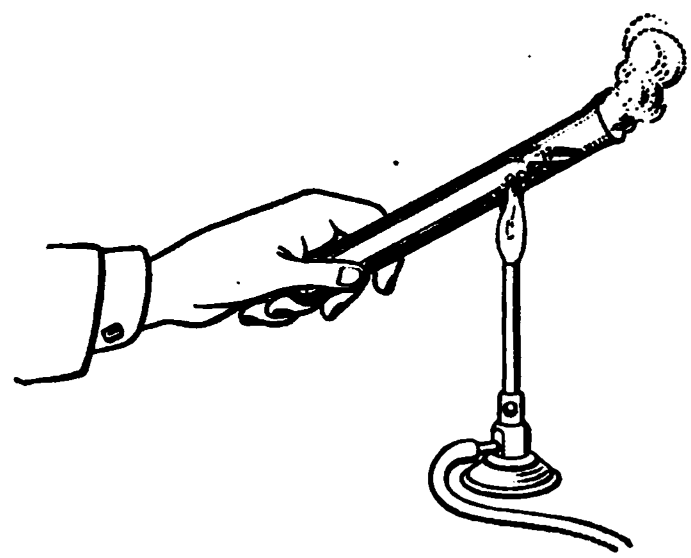


FIG. 194. Water a nonconductor

Careful measurements of the conductivity of water show that it is only about $\frac{1}{1200}$ of that of silver. The conductivity of gases is even less, not amounting on the average to more than $\frac{1}{25}$ that of water.

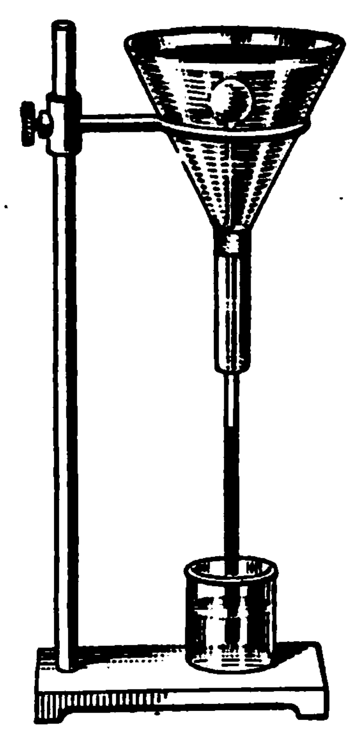


FIG. 195. Burning ether on the water does not affect the air thermometer

252. Conductivity and sensation. It is a fact of common observation that on a cold day in winter a piece of metal feels much colder to the hand than a piece of wood, notwithstanding the fact that the temperature of the wood must be the same as that of the metal. On the other hand, if the same two bodies had been lying in the hot sun in midsummer, the wood might be handled without discomfort, but the metal would be uncomfortably hot. The explanation of these phenomena is found in the fact that the iron, being a much better conductor than the wood, removes heat from

the hand much more rapidly in winter, and imparts heat to the hand much more rapidly in summer, than does the wood. In general, the better a conductor the hotter it will feel to a hand colder than itself, and the colder to a hand hotter than itself. Thus, in a cold room oilcloth, a fairly good conductor, feels much colder to the touch than a carpet, a comparatively poor conductor. For the same reason linen clothing feels cooler to the touch in winter than woolen goods.

253. The rôle of air in nonconductors. Feathers, fur, felt, etc. make very warm coverings, because they are very poor conductors of heat and thus prevent the escape of heat from the body. Their poor conductivity is due in large measure to the fact that they are full of minute spaces containing air, and gases are the best nonconductors of heat. It is for this reason that freshly fallen snow is such an efficient protection to vegetation. Farmers always fear for their fruit trees and vines when there is a severe cold snap in winter, unless there is a coating of snow on the ground to prevent a deep freezing.

254. The Davy safety lamp. Let a piece of wire gauze be held above an open gas jet and a match applied above the gauze. The flame will be found to burn above the gauze as in Fig. 196, (1), but it will not pass through to the lower side. If it is ignited below the gauze, the flame will not pass through to the upper side but will burn as shown in Fig. 196, (2).

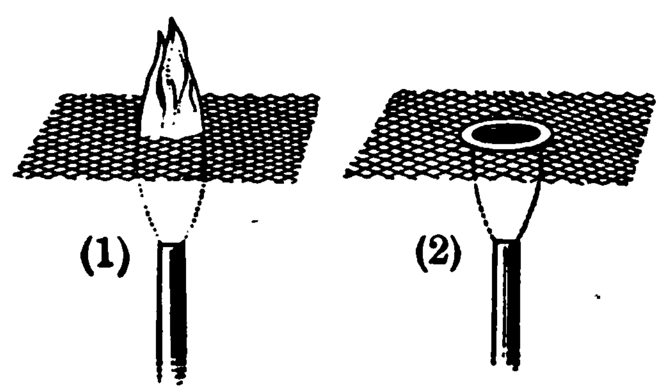


FIG. 196. A flame will not pass through wire gauze

The explanation is found in the fact that the gauze conducts the heat away from the flame so rapidly that the gas on the other side is not raised to the temperature of ignition. Safety lamps used by miners are completely incased in gauze, so that if the mine is full of inflammable gases, they are not ignited outside of the gauze by the lamp.

QUESTIONS AND PROBLEMS

1. With the aid of Fig. 197, which represents a fireless cooker, explain the principle on which fireless cooking is done.

2. Why do firemen wear flannel shirts in summer to keep cool and in winter to keep warm?

3. If a package of ice cream is put inside a paper bag, it will not melt so fast on a hot day. Explain.

4. If the ice in a refrigerator is wrapped up in blankets, what is the effect on the ice? on the refrigerator?

5. If a piece of paper is wrapped tightly around a metal rod and held for an instant in a Bunsen flame, it will not be scorched. If held in a flame when wrapped around a wooden rod, it will be scorched at once. Explain.

FIG. 197. A fireless cooker

6. If one touches the pan containing a loaf of bread in a hot oven, he receives a much more severe burn than if he touches the bread itself, although the two are at the same temperature. Explain.

7. Why are plants often covered with paper on a night when frost is expected?

8. Why will a moistened finger or the tongue freeze instantly to a piece of iron on a cold winter's day, but not to a piece of wood?

9. Does clothing ever afford us heat in winter? How, then, does it keep us warm?

10. Why is the outer pail of an ice-cream freezer made of thick wood and the inner can of thin metal?

CONVECTION

255. Convection in liquids. Although the conducting power of liquids is so small, as was shown in the experiment of § 251, they are yet able, under certain circumstances, to transmit heat much more effectively than solids. Thus, if the ice in the experiment of Fig. 194 had been placed at the top and the flame at the bottom, the ice would have been melted very quickly. This shows that heat is transferred very much

more readily from the bottom of the tube toward the top than from the top toward the bottom. The mechanism of this heat transference will be evident from the following experiment:

Let a round-bottomed flask (Fig. 198) be half filled with water and a few crystals of magenta dropped into it. Then let the bottom of the flask be heated with a Bunsen burner. The magenta will reveal the fact that the heat sets up currents the direction of which is upward in the region immediately above the flame but downward at the sides of the vessel. It will not be long before the whole of the water is uniformly colored. This shows how thorough is the mixing accomplished by the heating.

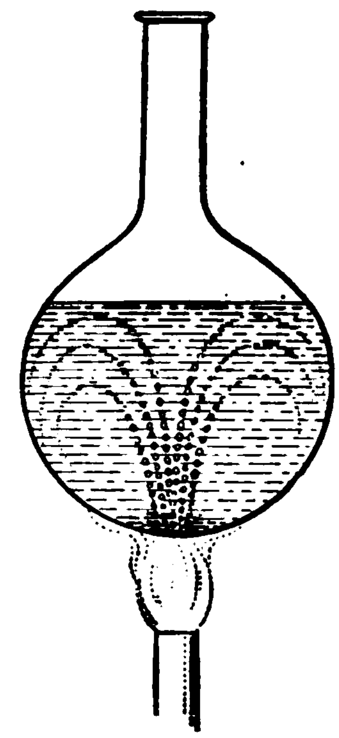


FIG. 198. Convection currents

The explanation of the phenomenon is as follows: The water nearest the flame became heated and expanded. It was thus rendered less dense than the surrounding water, and was accordingly forced to the top by the pressure transmitted from the colder and therefore denser water at the sides which then came in to take its place.

It is obvious that this method of heat transfer is applicable only to fluids. The essential difference between it and conduction is that the heat is not transferred from molecule to molecule throughout the whole mass, but is rather transferred by the bodily movement of comparatively large masses of the heated liquid from one point to another. This method of heat transference is known as *convection.*

256. Winds and ocean currents. Winds are convection currents in the atmosphere caused by unequal heating of the earth by the sun. Let us consider, for example, the land and sea breezes so familiar to all dwellers near the coasts of large bodies of water. During the daytime the land is heated more rapidly than the sea, because the specific heat of water is much greater than that of earth. Hence the hot air over the

land expands and is forced up by the colder and denser air over the sea which moves in to take its place. This constitutes the sea breeze, which blows during the daytime, usually reaching its maximum strength in the late afternoon. At night the earth cools more rapidly than the sea and hence the direction of the wind is reversed. The effect of these breezes is seldom felt more than twenty-five miles from shore.

Ocean currents are caused partly by the unequal heating of the sea and partly by the direction of the prevailing winds. In general, both winds and currents are so modified by the configuration of the continents that it is only over broad expanses of the ocean that the direction of either can be predicted from simple considerations.

Radiation

257. A third method of heat transference. There are certain phenomena in connection with the transfer of heat for which conduction and convection are wholly unable to account. For example, if one sits in front of a hot grate fire, the heat which he feels cannot come from the fire by convection, because the currents of air are moving toward the fire rather than away from it. It cannot be due to conduction, because the conductivity of air is extremely small and the colder currents of air moving toward the fire would more than neutralize any transfer outward due to conduction. There must therefore be some way in which heat travels across the intervening space other than by conduction or convection.

It is still more evident that there must be a third method of heat transfer when we consider the heat which comes to us from the sun. Conduction and convection take place only through the agency of matter; but we know that the space between the earth and the sun is not filled with ordinary matter, or else the earth would be retarded in its motion through space. *Radiation* is the name given to this third

method by which heat travels from one place to another, and which is illustrated in the passing of heat from a grate fire to a body in front of it, or from the sun to the earth.

258. The nature of radiation. The nature of radiation will be discussed more fully in Chapter XXI. It will be sufficient here to call attention to the following differences between conduction, convection, and radiation.

First, while conduction and convection are comparatively slow processes, the transfer of heat by radiation takes place with the enormous speed with which light travels, namely 186,000 miles per second. That the two speeds are the same is evident from the fact that at the time of an eclipse of the sun the shutting off of heat from the earth is observed to take place at the same time as the shutting off of light.

Second, radiant heat travels in straight lines, while conducted or convected heat may follow the most circuitous routes. The proof of this statement is found in the familiar fact that radiation may be cut off by means of a screen placed directly between a source and the body to be protected.

Third, radiant heat may pass through a medium without heating it. This is shown by the fact that the upper regions of the atmosphere are very cold, even in the hottest days in summer, or that a hothouse may be much warmer than the glass through which the sun's rays enter it.

259. The Dewar flask and the thermos bottle. For the retention of extremely cold liquids, such, for example, as liquefied air, whose boiling point is $-190°$ C. ($=-310°$ F.), Dewar invented a double-walled vessel. The space between the walls is a vacuum, and the inner surface of the outer vessel and the outer surface of the inner vessel are silvered. There are three ways in which heat may pass inward through the double wall — conduction, convection, and radiation. The vacuum prevents almost entirely the first two, while the silvering eliminates passage of heat by radiation. The well-known

glass part of the thermos bottle (Fig. 199) is simply a cylindrical Dewar flask for keeping liquids either hot or cold, since it is as difficult for heat to pass outward through the walls as to pass inward. The glass flask is provided with a cork stopper, and a strong outside metal case for its protection. Hot liquids, as well as those that are cold, may be kept for several hours in a thermos bottle with only a few degrees change in temperature.

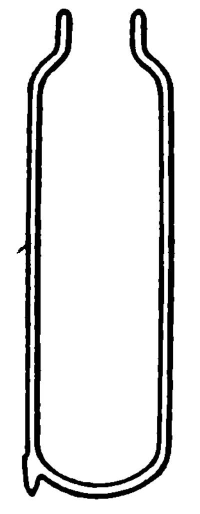


Fig. 199. The inner glass flask of a thermos bottle

The Heating and Ventilating of Buildings

260. The principle of ventilation. The heating and ventilating of buildings are accomplished chiefly through the agency of convection.

To illustrate the principle of ventilation let a candle be lighted and placed in a vessel containing a layer of water (Fig. 200). When a lamp chimney is placed over the candle so that the bottom of the chimney is under the water, the flame will slowly die down and will finally be extinguished. This is because the oxygen, which is essential to combustion, is gradually used up and nó fresh supply is possible with the arrangement described. If the chimney is raised even a very little above the water, the dying flame will at once brighten. Why? If a metal or cardboard partition is inserted in the chimney, as in Fig. 200, the flame will burn continuously, even when the bottom of the chimney is under water. The reason will be clear if a piece of burning touch paper (blotting paper soaked in a solution of potassium nitrate and dried) is held over the chimney. The smoke will show the direction of the air currents. If the chimney is a large one, in order that the first part of the above experiment may succeed, it may be necessary to use two candles; for too small a heated area permits the formation of downward currents at the sides.

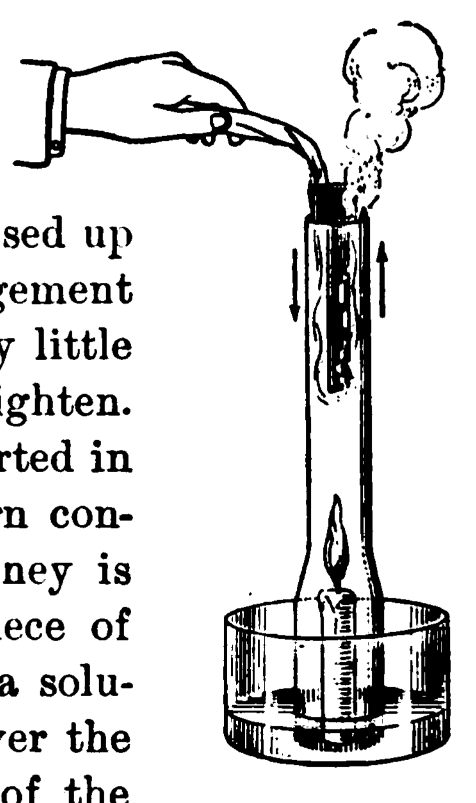


Fig. 200. Convection currents in air

261. Ventilation of houses. In order to secure satisfactory ventilation it is estimated that a room should be supplied with 2000 cubic feet of fresh air per hour for each occupant (a gas burner is equivalent in oxygen consumption to four persons). A current of air moving with a speed great enough to be just perceptible has a velocity of about 3 feet per second. Hence the area of opening required for each person when fresh air is entering at this speed is about 25 or 30 square inches. The manner of supplying this requisite amount of fresh air in dwelling houses depends upon the particular method of heating employed.

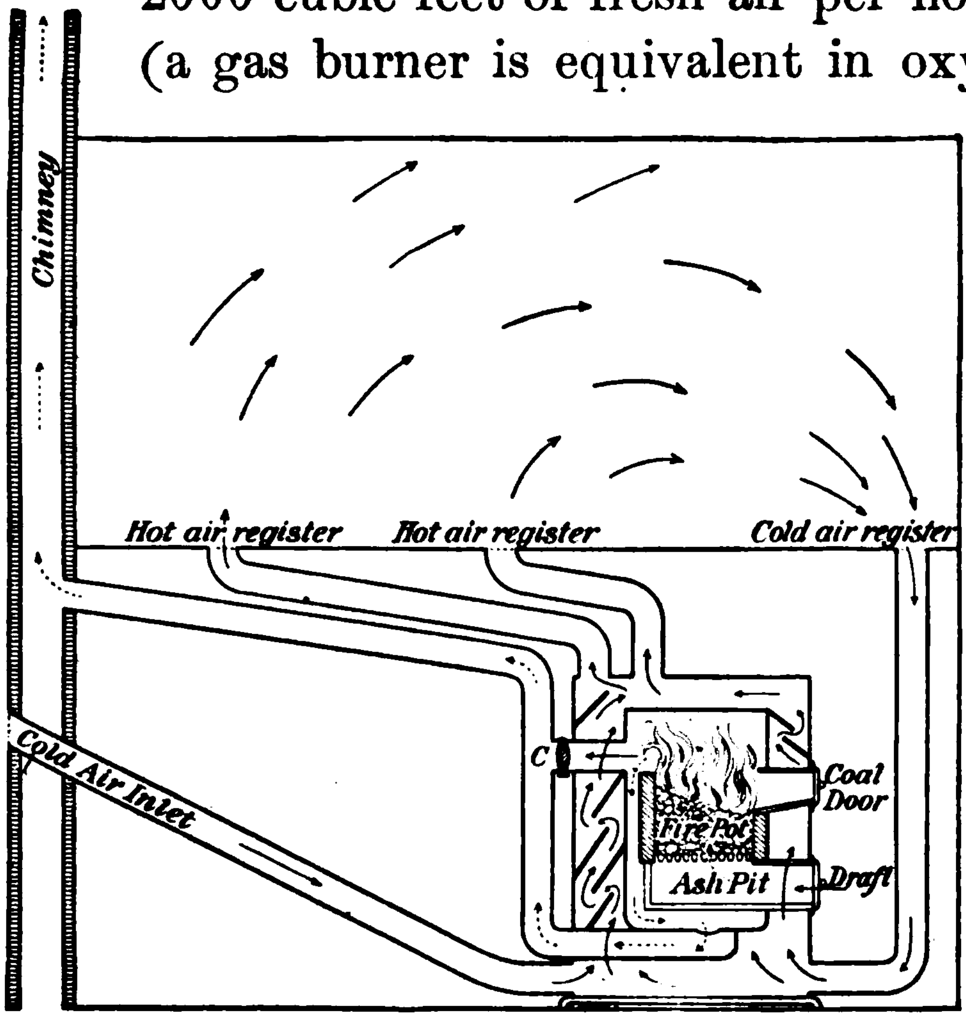


FIG. 201. Hot-air heating

If a house is heated by stoves or fireplaces, no special provision for ventilation is needed. The foul air is drawn up the chimney with the smoke, and the fresh air which replaces it finds entrance through cracks about the doors and windows and through the walls.

262. Hot-air heating. In houses heated by hot-air furnaces an air duct ought always to be supplied for the entrance of fresh cold air, in the manner shown in Fig. 201 (see "cold-air inlet"). This cold air from out of doors is heated by passing in a circuitous way, as shown by the arrows, over the outer jacket of iron which covers the fire box. It is then delivered to the

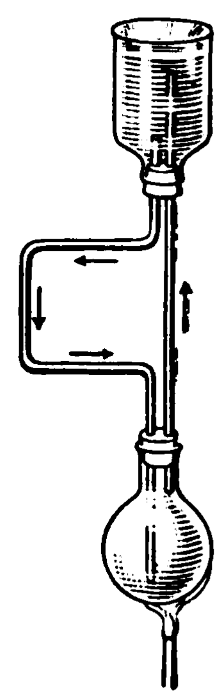


FIG. 202. Principle of hot-water heating

rooms. Here a part of it escapes through windows and doors, and the rest returns through the cold-air register to be reheated, after being mixed with a fresh supply from out of doors.

When the fire is first started, in order to gain a strong draft the damper *C* is opened so that the s
may pass directly up the chin
After the fire is under way the da
C is closed so that the smoke an

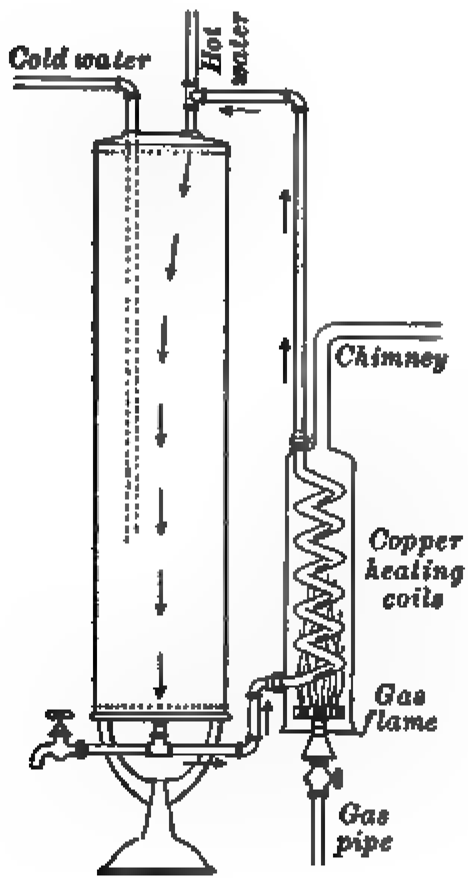


FIG. 203. A gas heating coil

FIG. 204. Hot-water heater

gases from the furnace must pass, as indicated by the dotted arrows, over a roundabout path, in the course of which they give up the major part of their heat to the steel walls of the jacket, which in turn pass it on to the air which is on its way to the living rooms.

263. Hot-water heating. To illustrate the principle of hot-water heating let the arrangement shown in Fig. 202 be set up, the upper vessel being filled with colored water, and then let a flame be applied to the lower vessel. The colored water will show that the current moves in the direction of the arrows.

This same principle is involved in the gas heating coil used in connection with the kitchen boiler (Fig. 203). Heat from the flame passes through the copper coil to the water, and convection begins as indicated by the arrows. When hot water is drawn from the top of the boiler, cold water enters near the bottom so as not to mingle with the hot water that is being used. The principle is still further illustrated by the cooling systems used for keeping automobile engines from becoming overheated. Heat passes from the engine into the water, which loses heat in circulating through the coils of the radiator.

The actual arrangement of boiler and radiators in one system of hot-water heating is shown in Fig. 204. The water heated in the furnace rises directly through the pipe *A* to a radiator *R*, and returns again to the bottom of the furnace through the pipes *B* and *D*. The circulation is maintained because the column of water in *A* is hotter and therefore lighter than the water in the return pipe *B*.

By eliminating the expansion tank and partly filling the boiler with water the system could be converted into a steam-heating plant.

QUESTIONS AND PROBLEMS

1. If we attempt to start a fire in the kitchen range when the chimney is cold and damp, the range "smokes." Explain.

2. Why is a hollow wall filled with sawdust a better nonconductor of heat than the same wall filled with air alone?

3. In a system of hot-water heating why does the return pipe always connect at the bottom of the boiler, while the outgoing pipe connects with the top?

4. Which is thermally more efficient, a cook stove or a grate? Why?

5. When a room is heated by a fireplace, which of the three methods of heat transference plays the most important rôle?

6. Why do you blow on your hands to warm them in winter and fan yourself for coolness in summer?

7. If you open a door between a warm and a cold room, in what direction will a candle flame be blown which is placed at the top of the door? Explain.

8. Why is felt a better conductor of heat when it is very firmly packed than when loosely packed?

9. If 2 metric tons of coal are burned per month in your house, and if your furnace allows one third of the heat to go up the chimney, how many calories remain to be used per day? (Take 1 g. as yielding 6000 calories. A metric ton = 1000 kg.)

CHAPTER XII

MAGNETISM*

General Properties of Magnets

264. Magnets. It has been known for many centuries that some specimens of the ore known as magnetite (Fe_3O_4) have the property of attracting small bits of iron and steel. This ore probably received its name from the fact that it was first observed in the province of Magnesia, in Thessaly. Pieces of this ore which exhibit this attractive property are known as *natural magnets.*

It was also known to the ancients that artificial magnets may be made by stroking pieces of steel with natural magnets, but it was not until about the twelfth century that the discovery was made that *a suspended magnet will assume a north-and-south position.* Because of this latter property natural magnets became known as lodestones (leading stones), and magnets, either artificial or natural, began to be used for determining directions. The first mention of the use of the compass in Europe is in 1190. It is thought to have been introduced from China. (See opposite p. 223 for the gyrocompass.)

Magnets are now made either by stroking bars of steel in one direction with a magnet, or by passing electric currents about the bars in a manner to be described later. The form shown in Fig. 205 is called a *bar magnet,* that shown in Fig. 206 a *horseshoe magnet.* The latter form is the more common, and is the better form for lifting.

*This chapter should be either accompanied or preceded by laboratory experiments on magnetic fields and on the molecular nature of magnetism. See, for example, Experiments 25 and 26 of the authors' Manual.

If a magnet is dipped into iron filings, the filings will be seen to cling in tufts near the ends but scarcely at all near the middle (Fig. 207). These places near the ends of a magnet at which its strength seems to be concentrated are called the *poles* of the magnet. The end of a freely swinging magnet which points to the north is designated as the north-seeking pole, or simply the *north pole* (*N*); and the other end as the south-seeking pole, or the *south pole* (*S*). *The direction in which a compass needle points is called the magnetic meridian.*

FIG. 205. A bar magnet

FIG. 206. A horseshoe magnet

265. The laws of magnetic attraction and repulsion. In the experiment with the iron filings no particular difference was observed between the action of the two poles. That there is a difference, however, may be shown by experimenting with two magnets, either of which may be suspended (see Fig. 208). If two *N* poles are brought near one another, they are found to repel each other. The *S* poles likewise are found to repel each other. But the *N* pole of one magnet is found to be attracted by the *S* pole of another. The results of these experiments may be summarized in a general law: *Magnet poles of like kind repel each other, while poles of unlike kind attract.*

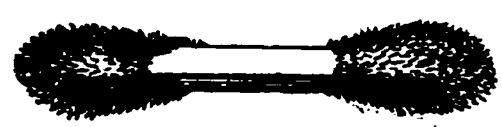


FIG. 207. Iron filings clinging to a bar magnet

The force which any two poles exert upon each other in air is equal to the product of the pole strengths divided by the square of the distance between them.

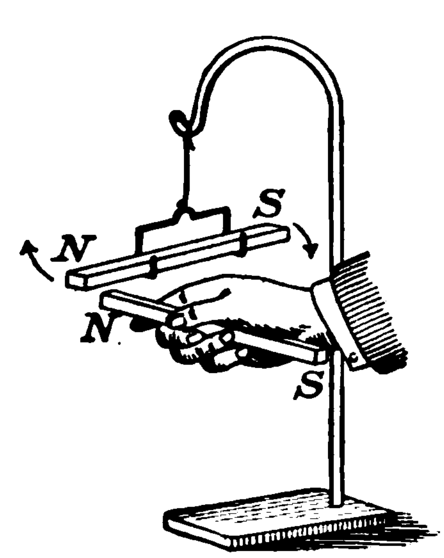


FIG. 208. Magnetic attractions and repulsions

A unit pole is defined as a pole which, when placed at a distance of 1 *centimeter from an exactly similar pole, in air, repels it with a force of* 1 *dyne.*

266. Magnetic materials. Iron and steel are the only substances which exhibit magnetic properties to any marked degree. Nickel and cobalt are also attracted appreciably by strong magnets. Bismuth, antimony, and a number of other substances are actually repelled instead of attracted, but the effect is very small. It has recently been found possible to make quite strongly magnetic alloys out of certain nonmagnetic materials. For example, a mixture of 65% copper, 27% manganese, and 8% aluminium is quite strongly magnetic. These are called Heusler alloys. For practical purposes, however, iron and steel may be considered as the only magnetic materials.

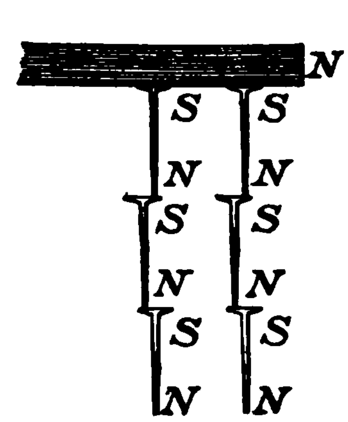


FIG. 209. Magnetism induced by contact

267. Magnetic induction. If a small unmagnetized nail is suspended from one end of a bar magnet, it is found that a second nail may be suspended from this first nail, which itself acts like a magnet, a third from the second, etc., as shown in Fig. 209. But if the bar magnet is carefully pulled away from the first nail, the others will instantly fall away from each other, thus showing that the nails were strong magnets only so long as they were in contact with the bar magnet. Any piece of soft iron may be thus magnetized *temporarily* by holding it in contact with a permanent magnet. Indeed, it is not necessary that there be actual contact, for if a nail is simply brought near to the permanent magnet it is found to become a magnet. This may be proved by presenting some iron filings to one end of a nail held near a magnet in the manner shown in Fig. 210. Even inserting a plate of glass, or of copper, or of any other material except iron between S and N will not change appreciably the number of filings which cling

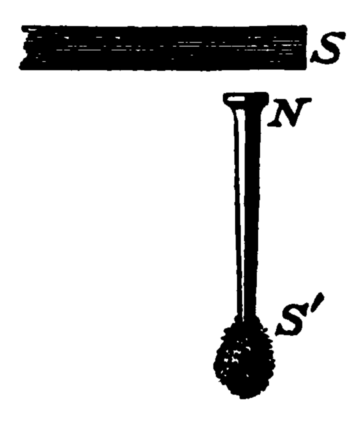


FIG. 210. Magnetism induced without contact

to the end of S', — a fact which shows that *nonmagnetic materials are transparent to magnetic forces.* But as soon as the permanent magnet is removed, most of the filings will fall. *Magnetism produced by the mere presence of adjacent magnets, with or without contact, is called induced magnetism.* If the induced magnetism of the nail in Fig. 210 is tested with a compass needle, it is found that the *remote* induced pole is of the same kind as the inducing pole, while the *near* pole is of unlike kind. This is the general law of magnetic induction.

Magnetic induction explains the fact that a magnet attracts an unmagnetized piece of iron, for it first magnetizes it by induction, so that the near pole is unlike the inducing pole, and the remote pole like the inducing pole; and then, since the two unlike poles are closer together than the like poles, the attraction overbalances the repulsion and the iron is drawn toward the magnet. Magnetic induction also explains the formation of the tufts of iron filings shown in Fig. 207, each little filing becoming a temporary magnet such that the end which points toward the inducing pole is unlike this pole, and the end which points away from it is like this pole. The bushlike appearance is due to the repulsive action which the outside free poles exert upon each other.

268. Retentivity and permeability. A piece of soft iron will very easily become a strong temporary magnet, but when removed from the influence of the magnet it loses practically all of its magnetism. On the other hand, a piece of steel will not be so strongly magnetized as the soft iron, but it will retain a much larger fraction of its magnetism after it is removed from the influence of the permanent magnet. This quality of resisting either magnetization or demagnetization is called *retentivity.* Thus steel has a much greater retentivity than wrought iron, and, in general, the harder the steel the greater its retentivity.

A substance which has the property of becoming strongly magnetic under the influence of a permanent magnet, whether it has a high retentivity or not, is said to possess *permeability* in large degree. Thus iron is much more permeable than nickel.

269. Magnetic lines of force. If we could separate the *N* and *S* poles of a small magnet so as to get an independent *N* pole, and were to place this *N* pole near the *N* pole of a bar magnet, it would move over to the *S* pole along some curved path similar to that shown in Fig. 211. The reason it would move in a curved path is that it would be simultaneously repelled by the *N* pole of the bar magnet and attracted by its *S* pole, and the relative strengths of these two forces would continually change as the relative distances of the moving pole from these two poles changed.

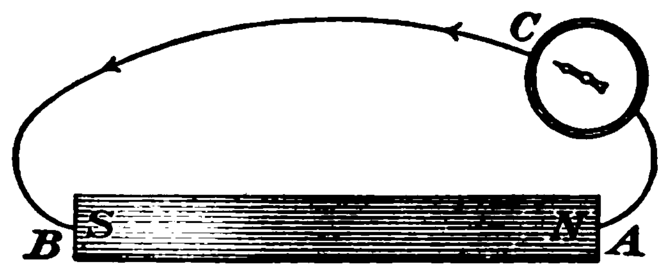


FIG. 211. A line of force set up by the magnet *AB*

To verify this conclusion let a strongly magnetized sewing needle be floated in a small cork in a shallow dish of water, and let a bar or horseshoe magnet be placed just above or just beneath the dish (see Fig. 212). The cork and needle will then move as would an independent pole, since the remote pole of the needle is so much farther from the magnet than the near pole that its influence on the motion is very small. The cork will actually be found to move in a curved path from *N* to *S*.

FIG. 212. Showing direction of motion of an isolated pole near a magnet

Any path which an independent *N* pole would take in going from *N* to *S* is called a *line of force*. The simplest way of finding the direction of this path at any point near a magnet is to hold a short compass needle at the point considered. The needle sets itself along the line in which its poles would move if independent, that is, along the line of force which passes through the given point (see *C*, Fig. 211).

270. Fields of force. The region about a magnet in which its magnetic forces can be detected is called its *field of force.* The easiest way of gaining an idea of the way in which the

FIG. 213. Arrangement of iron filings about a bar magnet

FIG. 214. Ideal diagram of field of a bar magnet

lines of force are arranged in the magnetic field about any magnet is to sift iron filings upon a piece of paper placed immediately over the magnet. Each little filing becomes a temporary magnet by induction, and therefore, like the compass needle, sets itself in the direction of the line of force at the point where it is. Fig. 213 shows how the filings arrange themselves about a bar magnet. Fig. 214 is the corresponding ideal diagram showing the lines of force emerging from the N pole and passing about in curved paths to the S pole. It is customary to imagine these lines as returning through the magnet from S to N in the manner shown, so that each line is thought of as a closed curve. This convention was introduced by Faraday, and has been found of great assistance in correlating the facts of magnetism.

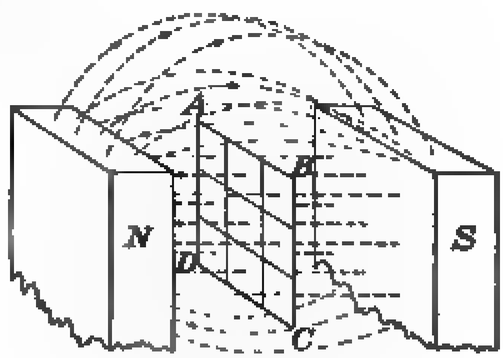


FIG. 215. The strength of a magnetic field is represented by the number of lines of force per square centimeter

A magnetic field of unit strength is defined as a field in which a unit magnet pole experiences 1 *dyne of force.* It is customary

to represent graphically such a field by drawing one line per square centimeter through a surface such as *ABCD* (Fig. 215) taken at right angles to the lines of force. If a unit *N* pole between *N* and *S* (Fig. 215) were pushed toward *S* with a force of 1000 dynes, the strength of the field would be 1000 units and it would be represented by 1000 lines per square centimeter.

271. Molecular nature of magnetism. If a small test tube full of iron filings be stroked from end to end with a magnet, it will be found to have become itself a magnet; but it will lose its magnetism as soon as the filings are shaken up. If a magnetized knitting needle is heated red-hot, it will be found to have lost its magnetism completely. Again, if such a needle is jarred, or hammered, or twisted, the strength of its poles, as measured by their ability to pick up tacks or iron filings, will be found to be greatly diminished.

These facts point to the conclusion that magnetism has something to do with the arrangement of the molecules, since causes which violently disturb the molecules of a magnet weaken its magnetism. Again, if a magnetized needle is broken, each part will be found to be a complete magnet; that is, two new poles will appear at the point of breaking, a new *N* pole on the part which has the original *S* pole, and a new *S* pole on the part which has the original *N* pole. The subdivision may be continued indefinitely, but always with the same result, as indicated in Fig. 216. This suggests that the molecules of a magnetized bar may themselves be little magnets arranged in rows with their opposite poles in contact.

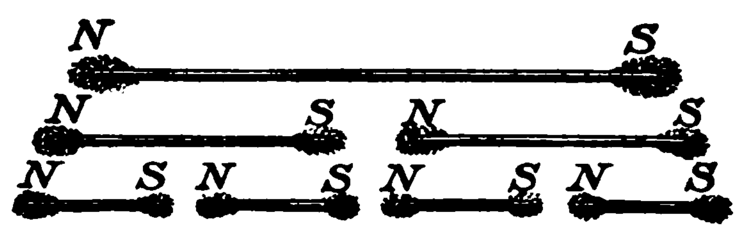


Fig. 216. Effect of breaking a magnet

If an unmagnetized piece of hard steel is pounded vigorously while it lies between the poles of a magnet, or if it is heated to redness and then allowed to cool in this position, it will be found to have become magnetized. This suggests that the

molecules of the steel are magnets even when the bar as a whole is not magnetized, and that magnetization may consist in causing them to arrange themselves in rows, end to end, just as the magnetization of the tube of iron filings mentioned above was due to a special arrangement of the filings.

272. Theory of magnetism. In an unmagnetized bar of iron or steel it is probable, then, that the molecules themselves are tiny magnets which are arranged either haphazard or in little closed groups or chains, as in Fig. 217, so that, on the whole, opposite poles neutralize each other throughout the bar. But when the bar is brought near a magnet, the molecules are swung around by the outside magnetic force into an arrangement somewhat like the one shown in Fig. 218, where the opposite poles completely neutralize each other only in the middle of the bar. According to this view, heating and jarring weaken the magnet because they tend to shake the molecules out of alignment. On the other hand, heating and jarring facilitate magnetization when the bar is between the poles of a magnet because they assist the magnetizing force in breaking up the molecular groups and chains and getting the molecules into alignment. Soft iron has higher permeability than hard steel, because the molecules of the former substance are much easier to swing into alignment than those of the latter substance. Steel has a very much greater retentivity than soft iron, because its molecules are not so easily moved out of position when once they have been aligned.

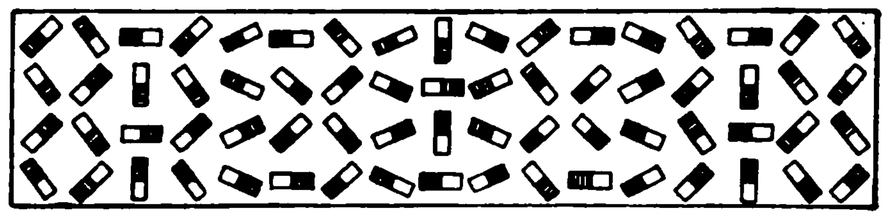


FIG. 217. Arrangement of molecules in an unmagnetized iron bar

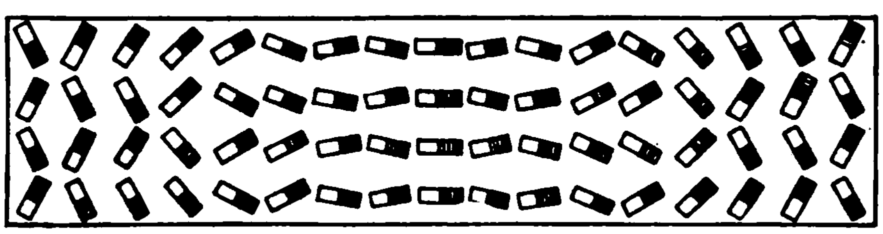


FIG. 218. Arrangement of molecules in a magnetized iron bar

273. Saturation. Strong evidence for the correctness of the above view is found in the fact that a piece of iron or steel cannot be magnetized beyond a certain limit, no matter how strong the magnetizing force is. This limit probably corresponds to the condition in which the axes of all the molecules are brought into parallelism, as in Fig. 219. The magnet is then said to be *saturated*, since it is as strong as it is possible to make it.

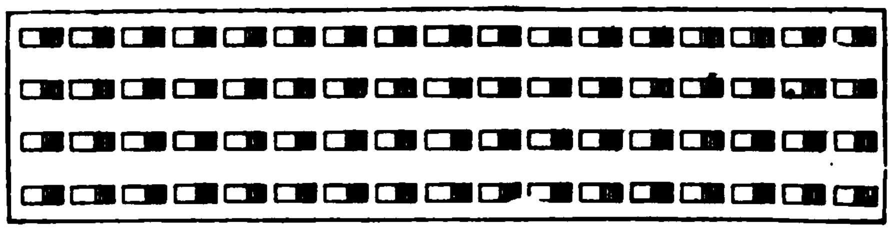


FIG. 219. Arrangement of molecules in a saturated magnet

TERRESTRIAL MAGNETISM

274. The earth's magnetism. The fact that a compass needle always points north and south, or approximately so, indicates that the earth itself is a great magnet having an *S* pole near the geographic north pole and an *N* pole near the geographic south pole; for the magnetic pole of the earth which is near the geographic north pole must of course be unlike the pole of a suspended magnet which points toward it, and the pole of the suspended magnet which points toward the north is the one which, by convention, it has been decided to call the *N* pole. The magnetic pole of the earth which is near the north geographic pole was found in 1831 by Sir James Ross in Boothia Felix, Canada, latitude 70° 30′ N., longitude 95° W. It was located again in 1905 by Captain Amundsen (the discoverer of the geographic south pole, 1912) at a point a little farther west. Its approximate location is 70° 5′ N. and 96° 46′ W. It is probable that it shifts its position slowly.

275. Declination. The earliest users of the compass were aware that it did not point exactly north; but it was Columbus who, on his first voyage to America, made the discovery, much to the alarm of his sailors, that the direction of the compass

William Gilbert (1540–1603)

English physician and physicist, first Englishman to appreciate fully the value of experimental observations; first to discover through careful experimentation that the compass points to the north not because of some influence of the stars, but because the earth is itself a great magnet; first to use the word "electricity"; first to discover that electrification can be produced by rubbing a great many different kinds of substances; author of the epoch-making book entitled "De Magnete, etc.," published in London in 1600

THE SPERRY GYROCOMPASS

Although the action of the mariner's compass was first correctly explained by Gilbert, the magnetic compass itself was invented by the Chinese and came to Europe about A.D. 1300. Until very recently it has been the sole reliance of the mariner. To-day, however, it has found a competitor in the gyrocompass, which is now used to a considerable extent on battleships, and exclusively on submarines, within whose encircling shell of iron the magnetic compass will not function at all. It consists of a heavy wheel driven 8600 revolutions per minute about a horizontal axis by an induction motor. Because of its inertia this wheel tends to maintain the plane of its rotation. The revolution of the earth, however, tends to make it leave this plane unless the axis of rotation of the gyro and the earth's axis are already in the same plane. This calls into play a couple which swings the axis of the gyro into the same plane with the axis of the earth

needle changes as one moves about over the earth's surface. The chief reason for this variation is found in the fact that the magnetic poles do not coincide with the geographic poles; but there are also other causes, such as the existence of large deposits of iron ore, which produce local effects upon the needle. The number of degrees by which at a given point on the earth the needle varies from a true north-and-south line is called its *declination* at that point. Lines drawn over the earth through points of equal declination are called *isogonic lines.*

276. The dipping needle. Let an unmagnetized knitting needle a (Fig. 220) be thrust through a cork, and let a second needle b be passed through the cork at right angles to a and as close to it as possible. Let a pin c be adjusted until the system is in neutral equilibrium about b as an axis, when a is pointing east and west. Then let a be carefully magnetized by stroking one end of it, from the middle out, with the N pole of a strong magnet, and the other end, from the middle out, with the S pole of the same magnet. If now the needle is replaced on its supports and turned into a north-and-south position, its N pole will be found to dip so as to cause the needle to make an angle of from 60° to 70° with the horizontal.

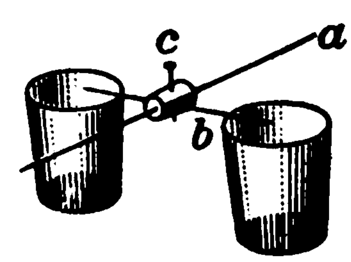


FIG. 220. Arrangement for showing dip

The experiment shows that in this latitude the earth's magnetic lines make a large angle with the horizontal. This angle between the earth's surface and the direction of the magnetic lines is called the *dip*, or *inclination*, of the needle. At Washington it is 71° 5′ and at Chicago 72° 50′. At the magnetic pole it is of course 90°, and at the so-called *magnetic equator*, which is an irregular curved line near the geographic equator, the dip is 0°.

277. The earth's inductive action. That the earth acts like a great magnet may be very strikingly shown in the following way:

Hold a steel rod (for example, a tripod rod) parallel to the earth's magnetic lines (the north end slanting down at an angle of about 70° or 75°) and strike it a few sharp blows with a hammer. The rod will

be found to have become a magnet with its upper end an S pole, like the north pole of the earth, and its lower end an N pole. If the rod is reversed and tapped again with the hammer, its magnetism will be reversed. If held in an east-and-west position and tapped, it will become demagnetized, as will be shown by the fact that either end of it will attract either end of a compass needle. In some respects a soft-iron rod is more satisfactory for this experiment than a steel rod, on account of the smaller retentivity.

QUESTIONS AND PROBLEMS

1. Make a diagram to show the general shape of the lines of force between unlike poles of two bar magnets; between like poles.

2. Devise an experiment which will show that a piece of iron attracts a magnet just as truly as the magnet attracts the iron.

3. In testing a needle with a magnet to see if the needle is magnetized why must you get *repulsion* before you can be sure it is magnetized?

4. A nail lies with its head near the N pole of a bar magnet. Diagram the nail and magnet, and draw from the N pole through the nail a *closed* curve to represent one line of force.

5. Explain, on the basis of induced magnetization, the process by which a magnet attracts a piece of soft iron.

6. Do the facts of induction suggest to you any reason why a horseshoe magnet retains its magnetism better when a bar of soft iron (a keeper, or armature) is placed across its poles than when it is not so treated? (See Fig. 218.)

7. Why should the needle used in the experiment of § 276 be placed east and west, when adjusting for neutral equilibrium, before it is magnetized?

8. How would an ordinary compass needle act if placed over one of the earth's magnetic poles? How would a dipping needle act at these points?

9. Why are the tops of steam radiators S magnetic poles, as proved by their invariable repulsion of the S pole of a compass?

10. Give two proofs that the earth is a magnet.

11. A magnetic pole of 80 units' strength is 20 cm. distant from a similar pole of 30 units' strength. Find the force between them.

CHAPTER XIII

STATIC ELECTRICITY

General Facts of Electrification

278. Electrification by friction. If a piece of hard rubber or a stick of sealing wax is rubbed with flannel or cat's fur and then brought near some dry pith balls, bits of paper, or other light bodies, these bodies are found to jump toward the rod. This sort of attraction, so familiar to us from the behavior of our hair in winter when we comb it with a rubber comb, was observed as early as 600 B.C., when Thales of Greece commented upon the fact that rubbed amber draws to itself threads and other light objects. It was not, however, until A.D. 1600 that Dr. William Gilbert, physician to Queen Elizabeth, and sometimes called the father of the modern science of electricity and magnetism, discovered that the effect could be produced by rubbing together a great variety of other substances besides amber and silk, such, for example, as glass and silk, sealing wax and flannel, hard rubber and cat's fur, etc.

Gilbert (see opposite p. 222) named the effect which was produced upon these various substances by friction *electrification*, after the Greek name *electron*, meaning "amber." *Thus, a body which, like rubbed amber, has been endowed with the property of attracting light bodies is said to have been electrified, or to have been given a charge of electricity.* In this statement nothing whatever is said about the nature of electricity. We simply define an electrically charged body as one which has been put into the condition in which it acts toward light bodies like the rubbed amber or the rubbed sealing wax. To

this day we do not know with certainty what the nature of electricity is, but we are fairly familiar with the laws which govern its action. The following sections deal with these laws.

279. Positive and negative electricity. Let a pith ball suspended by a silk thread, as in Fig. 221, be touched to a glass rod which has been rubbed with silk; the ball will thus be put into the condition in which it is strongly repelled by this rod. Next let a stick of sealing wax or an ebonite rod which has been rubbed with cat's fur or flannel be brought near the charged ball. It will be found that it is not repelled but, on the contrary, is very strongly attracted. Similarly, if the pith ball has touched the sealing wax so that it is repelled by it, it is found to be strongly attracted by the glass rod. Again, two pith balls both of which have been in contact with the glass rod are found to repel each other, while pith balls one of which has been in contact with the glass rod and the other with the sealing wax attract each other.

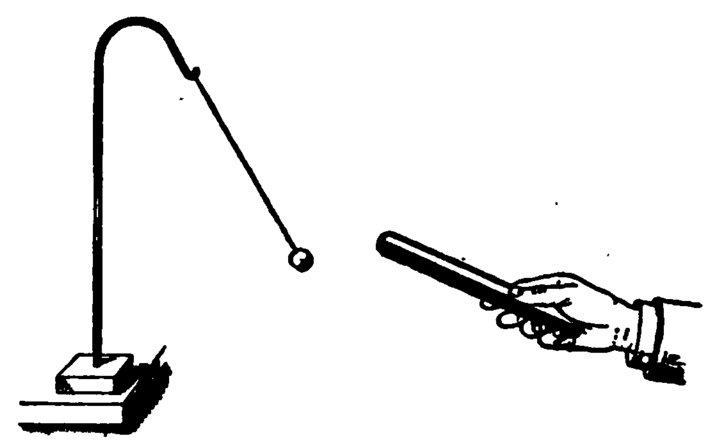


FIG. 221. Pith-ball electroscope

Evidently, then, the electrifications which are imparted to glass by rubbing it with silk and to sealing wax by rubbing it with flannel are opposite in the sense that an electrified body that is attracted by one is repelled by the other. We say, therefore, that there are two kinds of electrification, and we arbitrarily call one *positive* and the other *negative*. Thus, a *positively electrified body* is one which acts with respect to other electrified bodies like a *glass rod which has been rubbed with silk*, and a *negatively electrified body* is one which acts like a piece of *sealing wax which has been rubbed with flannel*. These facts and definitions may be stated in the following general law: *Electrical charges of like kind repel each other, while charges of unlike kind attract each other.* The forces of attraction or repulsion are found, like those of gravitation and magnetism, *to decrease as the square of the distance increases.*

280. Measurement of electrical quantities. The fact of attraction and repulsion is taken as the basis for the definition and measurement of so-called *quantities* of electricity. Thus, a small charged body is said to contain 1 unit of electricity when it will repel an exactly equal and similar charge placed 1 centimeter away with a force of 1 dyne. The number of units of electricity on any charged body is then measured by the force which it exerts upon a unit charge placed at a given distance from it; for example, a charge which at a distance of 10 centimeters repels a unit charge with a force of 1 dyne contains 100 units of electricity, for this means that at a distance of 1 centimeter it would repel the unit charge with a force of 100 dynes (see § 279).

281. Conductors and nonconductors. Let an electroscope *E* (Fig. 222), consisting of a pair of gold leaves *a* and *b*, suspended from an insulated metal rod *r* and protected from air currents by a case *J*, be connected with the metal ball *B* by means of a wire. Now let an ebonite rod be electrified and rubbed over *B*. The immediate divergence of the gold leaves will show that a portion of the electric charge placed upon *B* has been carried by the wire to the gold leaves, where it causes them to diverge in accordance with the law that bodies charged with the same kind of electricity repel each other.

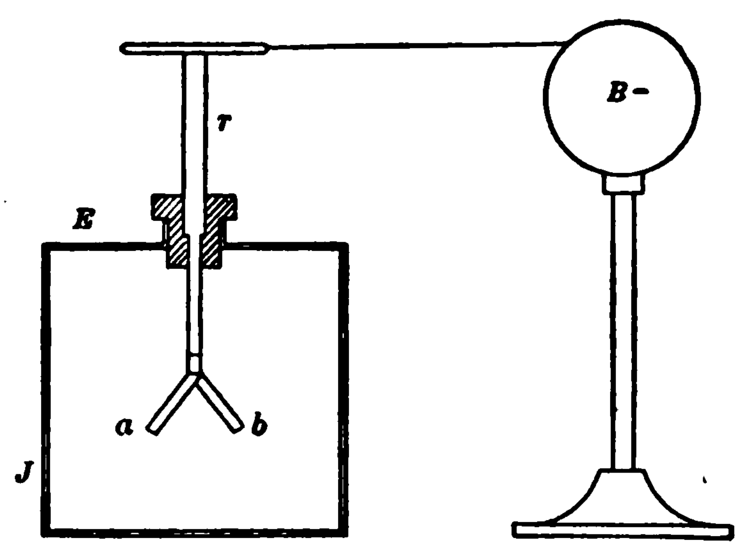


Fig. 222. Illustrating conduction

Let the experiment be repeated when *E* and *B* are connected with a thread of silk or a long rod of wood instead of the metal wire. No divergence of the leaves will be observed. If a moistened thread connects *E* and *B*, the leaves will be seen to diverge slowly when the ball *B* is charged, showing that a charge is carried slowly by the moist thread.

These experiments make it clear that while electric charges pass with perfect readiness from one point to another in a wire, they are quite unable to pass along dry silk or wood, and pass with difficulty along moist silk. We are therefore accustomed to divide substances into two classes, *conductors* and *nonconductors*, or *insulators*, according to their ability to transmit

electrical charges from point to point. Thus, metals and solutions of salts and acids in water are all conductors of electricity, while glass, porcelain, rubber, mica, shellac, wood, silk, vaseline, turpentine, paraffin, and oils are insulators. No hard-and-fast line, however, can be drawn between conductors and nonconductors, since all so-called insulators conduct to some slight extent, while the so-called conductors differ greatly in the facility with which they transmit charges.

The fact of conduction brings out sharply one of the most essential distinctions between electricity and magnetism. Magnetic poles exist only in iron and steel, while electrical charges may be communicated to any body whatever, provided it is insulated. These charges pass over conductors and can be transferred by contact from one body to any other, while magnetic poles remain fixed in position and are wholly uninfluenced by contact with other bodies, unless these bodies themselves are magnets.

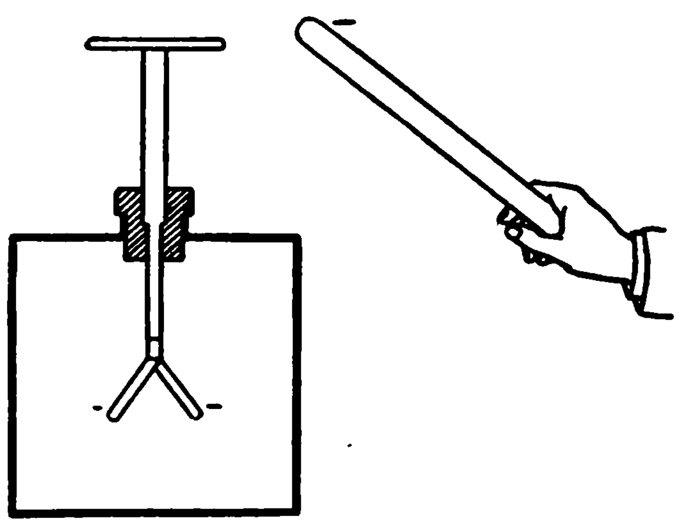


FIG. 223. Illustrating induction

282. Electrostatic induction. Let the ebonite rod be electrified by friction and slowly brought toward the knob of the gold-leaf electroscope (Fig. 223). The leaves will be seen to diverge, even though the rod does not approach to within a foot of the electroscope.

This makes it clear that the mere *influence* which an electric charge exerts upon a conductor placed in its neighborhood is able to produce electrification in that conductor. This method of producing electrification is called *electrostatic induction.*

As soon as the charged rod is removed, the leaves will be seen to collapse completely. This shows that this form of electrification is only a temporary phenomenon which is due simply to the presence of the charged body in the neighborhood.

283. Nature of electrification produced by induction. Let a metal ball A (Fig. 224) be strongly charged by rubbing it with a charged rod, and let it then be brought near an insulated* metal body B which is provided with pith balls or strips of paper a, b, c, as shown. The divergence of a and c will show that the ends of B have received electrical charges because of the presence of A, while the failure of b to diverge will show that the middle of B is uncharged. Further, the rod which charged A will be found to repel c but to attract a.

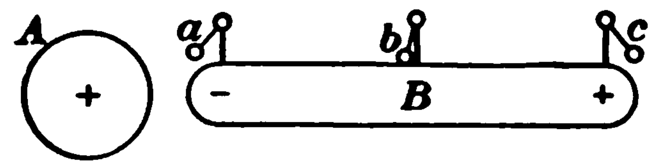


FIG. 224. Nature of induced charges

We conclude, therefore, that *when a conductor is brought near a charged body, the end away from the inducing charge is electrified with the same kind of electricity as that on the inducing body, while the end toward the inducing body receives electricity of the opposite kind.*

284. The electron theory of electricity. The atoms of all substances are now known to contain as constituents both positive and negative electricity, the latter existing in the form of minute corpuscles, or electrons, each of which has a mass $\frac{1}{1845}$ of that of the hydrogen atom. These electrons are probably grouped in some way about the positive electricity as a nucleus. The sum of the negative charges of these electrons is supposed to be just equal to the positive charge of the nucleus, so that in its normal condition the whole atom is neutral, or uncharged. But in conductors electrons are continually getting loose from the atoms and reëntering other atoms, so that at any given instant there are in every conductor a number of free negative electrons and a corresponding number of atoms which have lost electrons and which are therefore positively charged. Such a conductor would, as a whole, show no charge of either positive or negative electricity.

* Sulphur is practically a perfect insulator in all weathers, wet or dry. Metal conductors of almost any shape resting upon pieces of sulphur will serve the purposes of this experiment in summer or winter.

But as soon as a body charged, for example, positively (Fig. 224) is brought near such a conductor, the negatively charged electrons are attracted to the near end, leaving behind them the positively charged atoms, which are not free to move from their positions. On the other hand, if a negatively charged body is brought near the conductor, the negative electrons stream away and the near end is left with the immovable plus atoms. As soon as the inducing charge is removed, the conductor becomes neutral again, because the little negative corpuscles return to their former positions under the influence of the attraction of the positive atoms. This is the present-day picture of the mechanism of electrification by induction.

The charge of one electron is called the elementary electrical charge. Its value has recently been accurately measured. There are 2.095 billion of them in one of the units defined in § 280. *Every electrical charge consists of an exact number of these ultimate electrical atoms.*

285. Charging by induction. Let two metal balls or two eggshells, *A* and *B*, which have been gilded or covered with tin foil be suspended by silk threads and touched together, as in Fig. 225. Let a positively charged body *C* be brought near them. As described above, *A* and *B* will at once exhibit evidences of electrification; that is, *A* will repel a positively charged pith ball, while *B* will attract it. If *C* is removed while *A* and *B* are still in contact, the separated charges reunite and *A* and *B* cease to exhibit electrification. But if *A* and *B* are separated from each other while *C* is in place, *A* will be found to remain positively charged and *B* negatively charged. This may be proved either by the attractions and repulsions which they show for charged rods brought near them or by the effects which they produce upon a charged electroscope brought into their vicinity, the leaves of the latter falling together when it is brought near one and spreading farther apart when brought near the other.

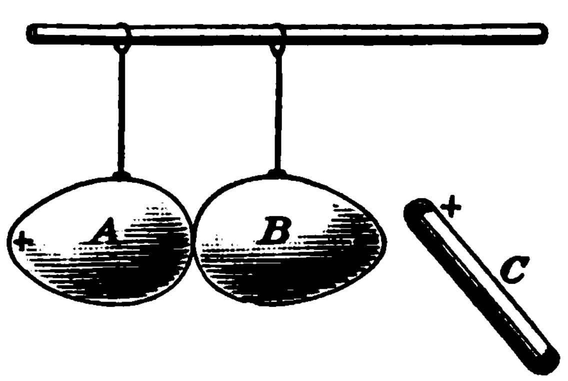
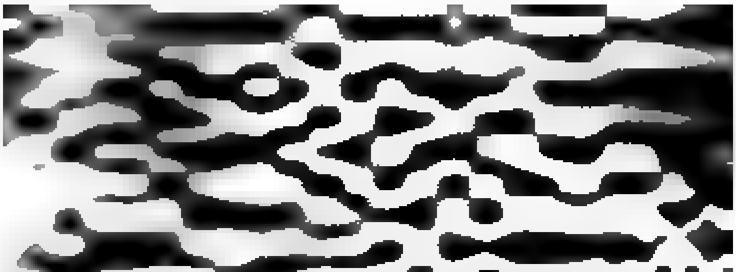


FIG. 225. Obtaining a plus and a minus charge by induction



BENJAMIN FRANKLIN (1706–1790)

Celebrated American statesman, philosopher, and scientist; born at Boston, the sixteenth child of poor parents; printer and publisher by occupation; pursued scientific studies in electricity as a diversion rather than as a profession; first proved that the two coats of a Leyden jar are oppositely charged; introduced the terms positive and negative electricity; proved the identity of lightning and frictional electricity by flying a kite in a thunderstorm and drawing sparks from the insulated lower end of the kite string; invented the lightning rod; originated the one-fluid theory of electricity which regarded a positive charge as indicating an excess, a negative charge a deficiency, in a certain normal amount of an all-pervading electrical fluid

FRANKLIN'S KITE EXPERIMENT

In June, 1752, Franklin demonstrated the identity of the electric spark and lightning. To prevent his kite from being torn in the rain he made it of a silk handkerchief. The lower end of the kite string and a silk ribbon were tied to the ring of a key, and, to prevent any charge that might appear upon the string and the key from escaping through his body to the earth, he held the kite by grasping the insulating silk ribbon. Standing under a shed to keep the ribbon dry, Franklin, by presenting his knuckle to the key, obtained sparks similar to those produced by his electric machine. With these sparks he charged his Leyden jar and used it to give a shock. Indeed, he performed with lightning all the experiments which he had previously performed with sparks from his frictional machine. The experiment is *dangerous* and should not be attempted by inexperienced persons

We see, therefore, that *if we cut in two, or separate into two parts, a conductor while it is under the influence of an electric charge, we obtain two permanently charged bodies, the remoter part having a charge of the same sign as that of the inducing charge, and the near part having a charge of unlike sign.* Under the influence of the positive charge on C the negative electrons moved out of A into B, which act made A positive and B negative.

Let the conductor B (Fig. 226) be touched at a by the finger while a charged rod C is near it. Then let the finger be removed and after it the rod C. If now a negatively charged pith ball is brought near B, it will be repelled, showing that B has become negatively charged. In this experiment the body of the experimenter corresponds to the egg A of the preceding experiment, and removing the finger from B corresponds to separating the two eggshells. Let the last experiment be repeated with only this modification, that B is touched at b rather than at a. When B is again tested with the pith ball, it will still be found to have a negative charge, exactly as when the finger was touched at a.

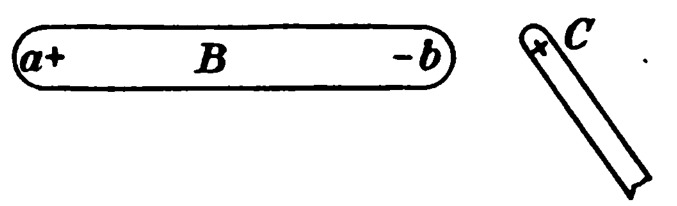


FIG. 226. A body charged by induction has a charge of sign opposite to that of the inducing charge

We conclude, therefore, that no matter where the body B is touched, *the sign of the charge left upon it is always opposite to that of the inducing charge.* This is because the negative electricity, that is, the electrons, can under no circumstances escape from b so long as C is present, for they are *bound* by the attraction of the positive charge on C. Indeed, the final negative charge on B is due merely to the fact that the positive charge on C pulls electrons into B from the finger, no matter where B is touched. In the same way, if C had been negative, it would have pushed electrons off from B through the finger and thus have left B positively charged.

286. Charging the electroscope by induction. Let an ebonite rod which has been rubbed with catskin be brought near the knob of the electroscope (Fig. 223). The leaves at once diverge. (Make a diagram of the electroscope with the negatively charged ebonite rod near the knob. By use of + and – signs explain the electrical condition of both the knob and the leaves.) Let the knob be touched with the finger while the rod is held in place. The leaves will fall together. (Explain by a diagram as before.) Let the finger be removed and then the rod. The leaves will fly apart again. (By a diagram explain the final electrical condition of both the knob and the leaves.)

The electroscope has been charged by induction, and since the charge on the ebonite rod was negative, the charge on the electroscope must be positive. If this conclusion is tested by bringing the charged ebonite rod near the electroscope, the leaves will fall together as the rod approaches the knob. How does this prove that the charge on the electroscope is positive? If the empty neutral hand approaches the knob, the leaves diverge less. Explain.

287. Plus and minus electricities always appear simultaneously and in equal amounts. Let an ebonite rod be completely discharged by passing it quickly through a Bunsen flame. Let a flannel cap having a silk thread attached be slipped over the rod, as in Fig. 227, and twisted rapidly around a number of times. When rod and cap together are held near a charged electroscope, no effect will be observed; but if the cap is pulled off, it will be found to be positively charged, while the rod will be found to have a negative charge.

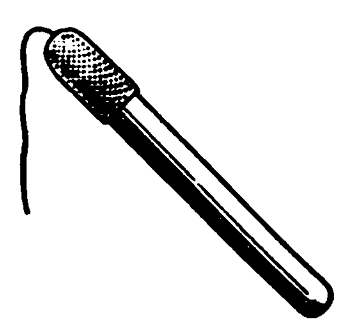


FIG. 227. Plus and minus electricities always developed in equal amounts

Since the two together produce no effect, the experiment shows that the plus and minus charges were equal in amount. This experiment confirms the view already brought forward in connection with induction, that electrification always consists in a separation of plus and minus charges which already exist in equal amounts within the bodies in which the electrification is developed.

QUESTIONS AND PROBLEMS

1. If pith balls, or any light figures, are placed between two plates (Fig. 228), one of which is connected to earth and the other to one knob of an electrical machine in operation, the figures will bound back and forth between the two plates as long as the machine is operated. Explain.

2. Given a gold-leaf electroscope, a glass rod, and a piece of silk, how, in general, would you proceed to test the sign of the electrification of an unknown charge?

FIG. 228

3. Charge a gold-leaf electroscope by induction from a glass rod. Warm a piece of paper and stroke it on the clothing. Hold it over the charged electroscope. If the divergence of the gold leaves is increased, is the charge on the paper + or −? If the divergence is decreased, what is the sign of the charge on the paper?

4. If you are given a positively charged insulated sphere, how could you charge two other spheres, one positively and the other negatively, without diminishing the charge on the first sphere?

5. If you bring a positively charged glass rod near the knob of an electroscope and then touch the knob, why do you not remove the negative electricity which is on the knob?

6. In charging an electroscope by induction, why must the finger be removed before the removal of the charged body?

7. If you hold a brass rod in the hand and rub it with silk, the rod will show no sign of electrification; but if you hold the brass rod with a piece of sheet rubber and then rub it with silk, you will find it electrified. Explain.

8. State as many differences as you can between the phenomena of magnetism and those of electricity.

9. If an electrified rod is brought near to a pith ball suspended by a silk thread, the ball is first attracted to the rod and then repelled from it. Explain this.

DISTRIBUTION OF ELECTRIC CHARGE UPON CONDUCTORS

288. Electric charges reside only upon the outside surface of conductors. Let a deep tin cup (Fig. 229) be placed upon an insulating stand and charged as strongly as possible either from an ebonite rod or from an electrical machine. If now a smooth metal ball suspended by a silk thread is touched to the *outside* of the charged cup and then brought near the knob of a charged electroscope, it will show a strong charge; but if it is touched to the *inside* of the cup, it will show no charge at all.

These experiments show that *an electric charge resides entirely on the outside surface of a conductor.* This is a result which might have been inferred from the fact that all the little electrical charges of which the total charge is made up repel each other and therefore move through the conductor until they are, on the average, as far apart as possible.

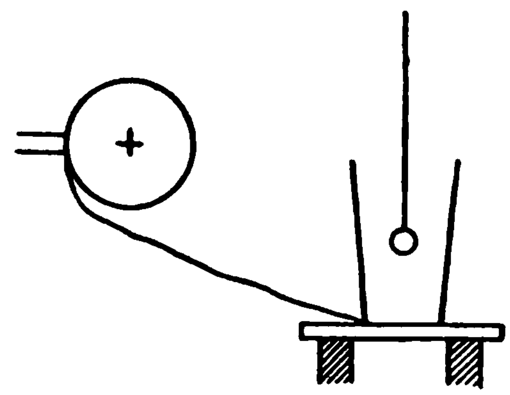


Fig. 229. Proof that charge resides on surface

289. Density of charge greatest where curvature of surface is greatest. Since all of the parts of an electric charge tend, because of their mutual repulsions, to get as far apart as possible, we should infer that if a charge of either sign is placed upon an oblong conductor like that of Fig. 230, (1), it will distribute itself so that the electrification at the ends will be stronger than that at the middle.

To test this inference let a proof plane — a flat metal disk (for example, a cent) provided with an insulating handle — be touched to one end of such a charged body, the charge conveyed to a gold-leaf electroscope, and the amount of separation of the leaves noted. Then let the experiment be repeated when the proof plane touches the middle of the body. The separation of the leaves in the latter case will be found to be very much less than in the former. If we should test the distribution on a pear-shaped body (Fig. 230, (2)) in the same way, we should find the density of electrification considerably greater on the small end than on the large one. By density of electrification is meant the quantity of electricity on unit area of the surface.

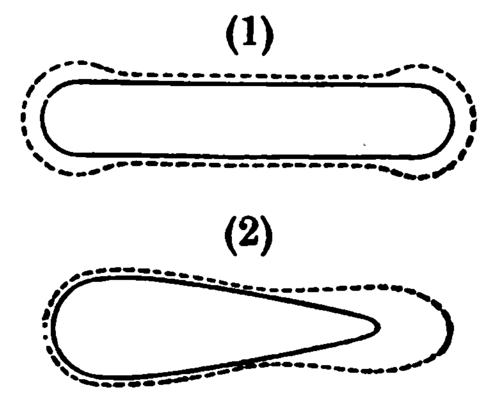


Fig. 230. Distribution of charge over oblong bodies

290. Discharging effect of points. The above experiments indicate that if one end of a pear-shaped body is made more and more pointed, then, when the body is charged, the electric

density on this end will become greater and greater. The following experiment will show what happens when the conductor is provided with a sharp point.

Let a very sharp needle be attached to any smooth insulated metal body provided with paper or pith-ball indicators, as in Fig. 224, p. 229. If the body is now charged either with a rubbed rod or with an electric machine, as soon as the supply of electricity is stopped the paper indicators will immediately fall, showing that the body is losing its charge. To show that this is certainly due to the effect of the point, remove the needle and repeat. The indicators will fall very slowly if at all.

The experiment shows that the electrical density upon the point is so great that the charge escapes from it into the air. This is because the intense charge on the point causes many of the adjacent molecules of the air to lose an electron. This leaves these molecules positively charged. The free electrons attach themselves to neutral molecules, thus charging them negatively. One set of these electrically charged molecules (called *ions*) is attracted to the point and the other repelled from it. The former set move to the conductor, give up their charges to it, and thus neutralize the charge upon it.

The effect of points may be shown equally well by charging the gold-leaf electroscope and holding a needle in the hand within a few inches of the knob. The leaves will fall together rapidly. In this case the needle point becomes electrified by induction and discharges to the knob electricity of the opposite kind to that on the knob, thus neutralizing its charge. An entertaining variation of the last experiment is to attach a tassel of tissue paper to an insulated conductor and electrify it strongly. The paper streamers under their mutual repulsions will stand out in all directions, but as soon as a needle point is held in the hand near them, they will fall together (Fig. 231), being discharged as described above.

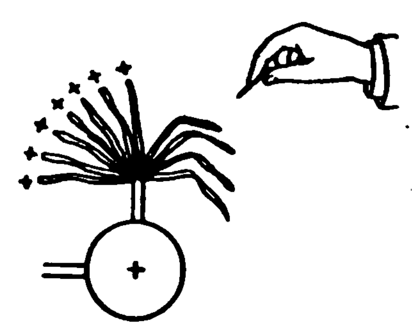


Fig. 231. Discharging effect of points

291. The electric whirl. Let an electric whirl (Fig. 232) be balanced upon a pin point and attached to one knob of an electric machine. As soon as the machine is started, the whirl will rotate rapidly in the direction of the arrows.

The explanation is as follows: The air close to each point is *ionized*, as explained in § 290. The ions of sign unlike that of the charge on the point are drawn to the point and discharged. The other set of ions is repelled. But since this repulsion is mutual, the point is pushed back with the same force with which these ions are pushed forward; hence the rotation. The repelled ions in their turn drag the air with them in their forward motions and thus produce the "electric wind," which may be detected easily by the hand or by a candle flame (Fig. 233).

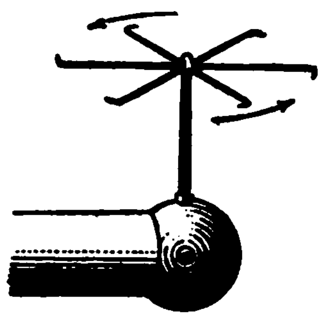


FIG. 232. The electric whirl

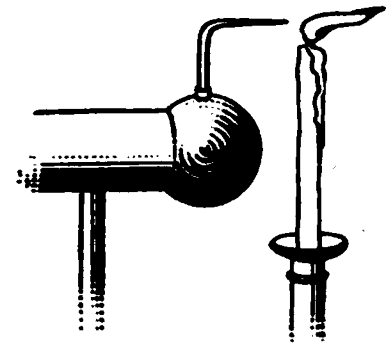


FIG. 233. The electric wind

292. Lightning and lightning rods. It was in 1752 that Franklin (see opposite p. 230), during a thunderstorm, sent up his historic kite (see opposite p. 231). This kite was provided with a pointed wire at the top. As soon as the hempen kite-string had become wet he succeeded in drawing ordinary electric sparks from a key attached to the lower end. This experiment demonstrated for the first time that thunderclouds carry ordinary electrical charges which may be drawn from them by points, just as the charge was drawn from the tassel in the experiment of § 290. It also showed that lightning is nothing but a huge electric spark. Franklin applied this discovery in the invention of the lightning rod. The way in which the rod discharges the cloud and protects the building is as follows: As the charged cloud approaches the building it induces an opposite charge in the rod. This induced charge escapes rapidly and quietly from the sharp point in the manner explained above and thus neutralizes the charge of the cloud.

To illustrate, let a metal plate C (Fig. 234) be supported above a metal ball E, and let C and E be attached to the two knobs of an electrical machine. When the machine is started, sparks will pass from C to E.

But if a point p is connected to E, the sparking will cease; that is, the point will protect E from the discharges, even though the distance Cp be considerably greater than CE.

The lower end of a lightning rod should be buried deep enough so that it will always be surrounded by moist earth, since dry earth is a poor conductor. It will be seen, therefore, that lightning rods protect buildings not because they conduct the lightning to earth, but because they prevent the formation of powerful charges in the neighborhood of the buildings on which they are placed.

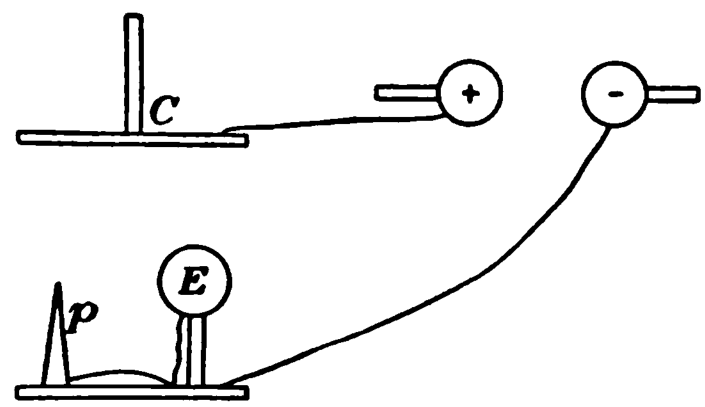


FIG. 234. Illustrating the action of a lightning rod

Flashes of lightning over a mile long have frequently been observed. Thunder is due to the violent expansion of heated air along the path of discharge. The roll of thunder is due to reflections from clouds, hills, etc.*

POTENTIAL AND CAPACITY

293. Potential difference. There is a very instructive analogy between the use of the word "potential" in electricity and "pressure" in hydrostatics. For example, if water will flow from tank A to tank B through the connecting pipe R (Fig. 235), we infer that the hydrostatic pressure at a must be greater than that at b, and we attribute the flow directly to this difference in pressure. In exactly the same way, if, when two bodies A and B (Fig. 236) are connected by a conducting wire r, a charge of + electricity

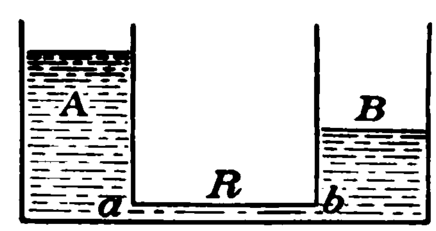


FIG. 235. Illustrating hydrostatic pressure

* A laboratory exercise on static electrical effects should follow the discussion of this section. See, for example, Experiment 27 of the authors' Manual.

is found to pass from A to B (that is, if electrons are found to pass from B to A) we say that the electrical potential is higher at A than at B, and we assign this *difference of potential* as the cause of the flow.* Thus, just as water tends to flow from points of higher hydrostatic pressure to points of lower hydrostatic pressure, so electricity tends to flow from points of higher electrical pressure, or potential, to points of lower electrical pressure, or potential.

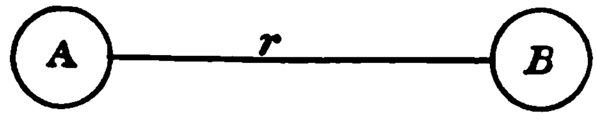


FIG. 236. Illustrating electrical pressure

Again, if water is not continuously supplied to one of the tanks A or B of Fig. 235, we know that the pressures at a and b must soon become the same. Similarly, if no electricity is supplied to the bodies A and B of Fig. 236, their potentials very quickly become the same. In other words, *all points on a system of connected conductors in which the electricity is in a stationary, or static, condition are at the same potential.* This result follows at once from the fact of mobility of electric charges through conductors.

But if water is continuously poured into A and removed from B (Fig. 235), the pressure at a will remain permanently above the pressure at b, and a continuous flow of water will take place through R. So, if A (Fig. 236) is connected with an electrical machine and B to earth, a permanent potential difference will exist between A and B, and a continuous current of electricity will flow through r. Difference in potential is commonly denoted simply by the letters P. D. (Potential Difference).

* Franklin thought that it was the positive electricity which moved through a conductor, while he conceived the negative as inseparably associated with the atoms. Hence it became a universally recognized convention to regard electricity as moving through a conductor in the direction in which a + charge would have to move in order to produce the observed effect. It is not desirable to attempt to change this convention now, even though the electron theory has exactly inverted the rôles of the + and − charges.

294. Some methods of measuring potentials. The simplest and most direct way of measuring the potential difference between two bodies is to connect one to the knob, the other to the conducting case,* of an electroscope. The amount of separation of the gold leaves is a measure of the P.D. between the bodies. The unit in which P.D. is usually expressed is called the *volt*. It will be accurately defined in § 334. It will be sufficient here to say that it is approximately equal to the electrical pressure between the ends of copper and zinc strips when dipped in dilute sulphuric acid or to two thirds of the electrical pressure between the zinc and carbon terminals of the familiar dry cell.

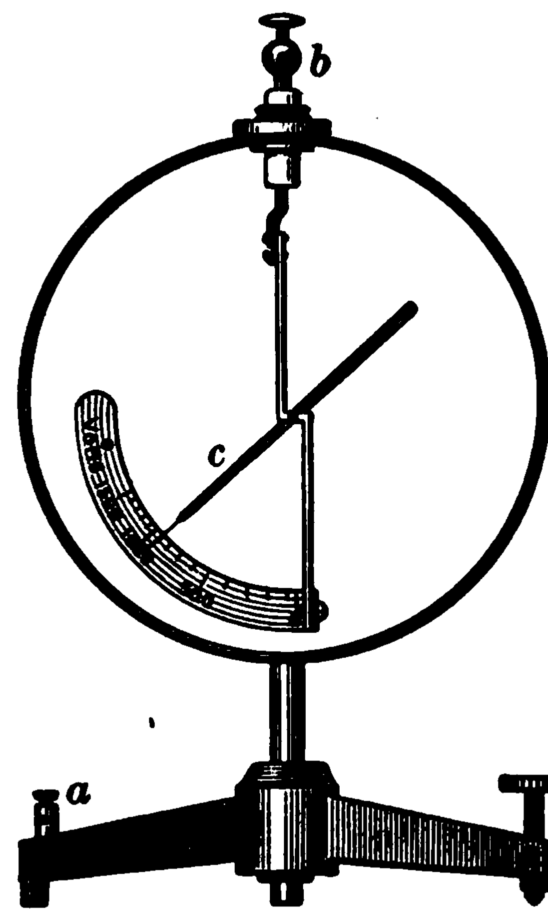


FIG. 237. Electrostatic voltmeter

Since the earth is, on the whole, a good conductor, its potential is everywhere the same (§ 293); hence it makes a convenient standard of reference in potential measurements. To find the potential of a body relative to that of the earth, we connect the outer case of the electroscope to the earth by means of a wire, and connect the body to the knob. If the electroscope is calibrated in volts, its reading gives the P.D. between the body and the earth. Such calibrated electroscopes are called *electrostatic voltmeters*. They are the simplest and in many respects the most satisfactory forms of voltmeters to be had. Their use, both in laboratories

* If the case is of glass, it should always be made conducting by pasting tin-foil strips on the inside of the jar opposite the leaves and extending these strips over the edge of the jar and down on the outside to the conducting support on which the electroscope rests. The object of this is to maintain the walls always at the potential of the earth.

and in electrical power plants, is rapidly increasing. They can be made to measure a P.D. as small as $\frac{1}{1000}$ volt and as large as 200,000 volts. Fig. 237 shows one of the simpler forms. The outer case is of metal and is connected to earth at the point *a*. The body whose potential is sought is connected to the knob *b*. This is in metallic contact with the light aluminium vane *c*, which takes the place of the gold leaf.

A very convenient way of measuring a *large* P.D. without a voltmeter is to measure the length of the spark which will pass between the two bodies whose P.D. is sought. The P.D. is roughly proportional to spark length, each centimeter of spark length representing a P.D. of about 30,000 volts if the electrodes are large compared to their distance apart.

295. Condensers. Let a metal plate *A* be mounted on an insulating base and connected with an electroscope, as in Fig. 238. Let a second plate *B* be similarly mounted and connected to the earth by a conducting wire. Let *A* be charged and the deflection of the gold leaves noted. If now we push *B* toward *A*, we shall observe that, as it comes near, the leaves begin to fall together, showing that the potential of *A* is diminished by the presence of *B*, although the quantity of electricity on *A* has remained unchanged. If we convey additional – charges to *A* with the aid of a proof plane, we shall find that many times the original amount of electricity may now be put on *A* before the leaves return to their original divergence, that is, before the body regains its original potential.

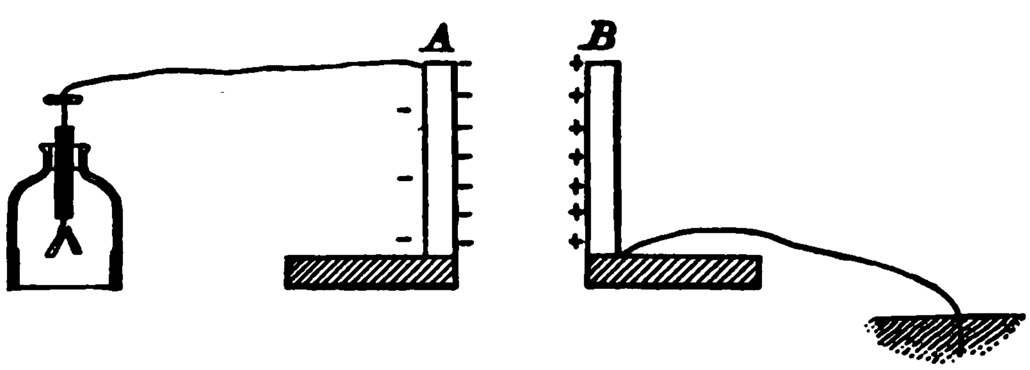


FIG. 238. The principle of the condenser

We say, therefore, that the *capacity* of *A* for holding electricity has been very greatly increased by bringing near it another conductor which is connected to earth. It is evident from this statement that *we measure the capacity of a body by the amount of electricity which must be put upon it to raise it to*

Count Alessandro Volta (1745–1827)

Great Italian physicist, professor at Como and at Pavia; inventor of the electroscope, the electrophorus, the condenser, and the voltaic pile (a form of galvanic cell); first measured the potential differences arising from the contact of dissimilar substances; ennobled by Napoleon for his scientific services; the volt, the practical unit of potential difference, is named in his honor

A MODERN HIGH-TENSION TOWER ON THE SOUTHERN CALIFORNIA EDISON COMPANY'S BIG CREEK LINE

These wires carry an alternating current having a potential of 150,000 volts. The current is generated by four 17,500-kilowatt dynamos driven by 8 Pelton water wheels operating under a head of 1900 feet and developing a horse power of 100,000. Even in wet weather the under surfaces of the series of nine petticoat insulators from which each wire is hung remain sufficiently dry to prevent large leakage losses. The wires are spaced 16 feet apart

a given potential. The explanation of the increase in capacity in this case is obvious. As soon as B was brought near to A it became charged, by induction, with electricity of opposite sign to A, the electricity of like sign to A being driven off to earth through the connecting wire. The attraction between these opposite charges on A and B drew the electricity on A to the face nearest to B and removed it from the more remote parts of A, so that it became possible to put a very much larger charge on A before the tendency of the electricity on A to pass over to the electroscope became as great as it was at first, that is, before the potential of A rose to its initial value. In such a condition the electricity on A is said to be *bound* by the opposite electricity on B.

An arrangement of this sort consisting of two conductors separated by a nonconductor is called a condenser. If the conducting plates are very close together and one of them grounded, the capacity of the system may be thousands of times as great as that of one of the plates alone.

296. The Leyden jar. The most common form of condenser is a glass jar coated part way to the top inside and outside with tin foil (Fig. 239). The inside coating is connected by a chain to the knob, while the outside coating is connected to earth. Condensers of this sort first came into use in Leyden, Holland, in 1745. Hence they are now called *Leyden jars.*

FIG. 239. The Leyden jar

To charge a Leyden jar the outer coating is held in the hand while the knob is brought into contact with one terminal of an electrical machine, — for example, the negative. As fast as electrons pass to the knob they spread to the inner coat of the jar, where they repel electrons from the outer coat to the earth, thus leaving it positively charged. If the inner and outer coatings are now connected by a discharging rod,

as in Fig. 239, a powerful spark will be produced. This spark is due to the rush of electrons from the − coat to the + coat. Let a charged jar be placed on a glass plate so as to insulate the outer coat. Let the knob be touched with the finger; no appreciable discharge will be noticed. Let the outer coat be in turn touched with the finger; again no appreciable discharge will appear. But if the inner and outer coatings are connected with the discharger, a powerful spark will pass.

The experiment shows that it is impossible to discharge one side of the jar alone, for practically all of the charge is bound by the opposite charge on the other coat. The full discharge can therefore occur only when the inner and outer coats are connected.

Leyden jars and other forms of condensers are of great practical use. They are used, for instance, in certain systems of telephony and telegraphy, in wireless communication, and in electrostatic machines and induction coils.

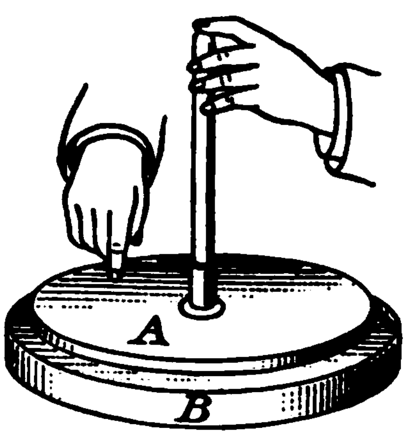


FIG. 240. The electrophorus

297. The electrophorus. The electrophorus is a simple electrical generator which illustrates well the principle underlying the action of all electrostatic machines. All such machines generate electricity primarily by induction, not by friction. *B* (Fig. 240) is a hard-rubber plate which is first charged by rubbing it with fur or flannel. *A* is a metal plate provided with an insulating handle. When the plate *A* is placed upon *B*, touched with the finger, and then removed, it is found possible to draw a spark from it, which in dry weather may be a quarter of an inch or more in length. The process may be repeated an indefinite number of times without producing any diminution in the size of the spark which may be drawn from *A*.

If the sign of the charge on *A* is tested by means of an electroscope, it will be found to be positive. This proves that *A* has been charged by induction, not by contact with *B*, for it is to be remembered that the latter is charged negatively. The reason for this is that even when *A* rests upon *B* it is in reality separated from it, at all but a very few

points, by an insulating layer of air; and since *B* is a non-conductor, its charge cannot pass off appreciably through these few points of contact. It simply repels negative electrons to the top side of the metal plate *A*, and thus charges positively the lower side. The electrons pass off to earth when the plate is touched with the finger. Hence, when the finger is removed and *A* lifted, it possesses a strong positive charge. Every commercial electrostatic machine is simply a continuously acting electrophorus which generates electricity by induction, not by friction.

QUESTIONS AND PROBLEMS

1. If you set a charged Leyden jar on a cake of paraffin, why can you not discharge it by touching one of the coatings?

2. Will a solid sphere hold a larger charge of electricity than a hollow one of the same diameter?

3. Why cannot a Leyden jar be appreciably charged if the outer coat is insulated?

4. With a stick of sealing wax and a piece of flannel, in what two ways could you give a positive charge to an insulated body?

5. Explain, using a set of drawings, the charging of the cover of an electrophorus.

6. Represent by a drawing the electrical condition of a tower just before it is struck by lightning, assuming the cloud at this particular time to be powerfully charged with + electricity.

7. When a negatively electrified cloud passes over a house provided with a lightning rod, the rod discharges positive electricity into the cloud. Explain.

CHAPTER XIV

ELECTRICITY IN MOTION *

Detection of Electric Currents

298. Electricity in motion produces a magnetic effect. Let a powerfully charged Leyden jar be discharged through a coil which surrounds an unmagnetized knitting needle, insulated by a glass tube, in the manner shown in Fig. 241, the compass needle being at rest in the position shown. After the discharge the knitting needle will be found to be distinctly magnetized. If the sign of the charge on the jar is reversed, the direction of deflection and the poles will in general be reversed.

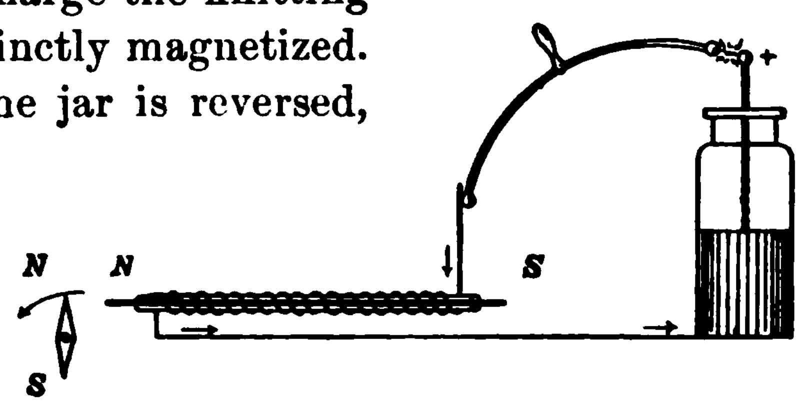


Fig. 241. Magnetic effect of an electric current produced from a static charge

The experiment shows that there is a definite connection between electricity and magnetism. Just what this connection is we do not yet know with certainty, but we do know that magnetic effects are always observable near the path of a moving electrical charge, while no such effects can ever be observed near a charge at rest.

To prove that a charge at rest does not produce a magnetic effect, let a charged body be brought near a compass needle. It will attract either end of the needle with equal readiness. While the needle is deflected, insert between it and the charge a sheet of zinc, aluminium, brass, or copper. This will act as an electric screen and will therefore cut off all effect of the charge. The compass needle will at once swing back to its north-and-south position.

* This chapter should be accompanied or, better, *preceded* by laboratory experiments on the simple cell and on the magnetic effects of a current. See, for example, Experiments 28, 29, and 30 of the authors' Manual.

Let the compass needle be deflected by a bar magnet, and let the screen be inserted again. The sheet of metal does not cut off the magnetic forces in the slightest degree.

The fact that an electric charge exerts no magnetic force is shown, then, both by the fact that it attracts either end of the compass needle with equal readiness and by the fact that the screen cuts off its action completely, while the same screen does not have any effect in cutting off the magnetic force.

An electrical charge in motion is called an electric current, and its presence is most commonly detected by the magnetic effect which it produces. A current of electricity is now considered to be a stream of negative electrons (see § 293).

299. The galvanic cell. When a Leyden jar is discharged, only a very small quantity of electricity passes through the connecting wires, since the current lasts for but a small fraction of a second. If we could keep a current flowing continuously through the wire, we should expect the magnetic effect to be much more pronounced. It was in 1786 that Galvani, an Italian anatomist at the University of Bologna, accidentally discovered that there is a chemical method for producing such a continuous current. His discovery was not understood, however, until Volta (see opposite p. 240), while endeavoring to throw light upon it, in 1800 invented an arrangement which is now known sometimes as the *voltaic* and sometimes as the *galvanic* cell. This consists, in its simplest form, of a strip of copper and a strip of zinc immersed in dilute sulphuric acid (Fig. 242).

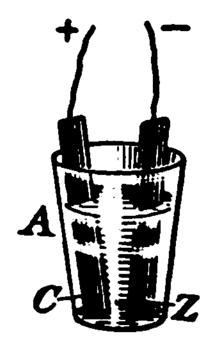


FIG. 242. Simple voltaic cell

Let the terminals of such a cell be connected for a few seconds to the ends of the coil of Fig. 241 when an unmagnetized needle lies within the glass tube. The needle will be found to have become magnetized much more strongly than before. Again, let the wire which connects the terminals of the cell be held above a magnetic needle, as in Fig. 243; the needle will be strongly deflected.

Evidently, then, the wire which connects the terminals of a galvanic cell carries a current of electricity. Historically the second of these experiments, performed by the Danish physicist Oersted (see on opposite page) in 1820, preceded the discovery of the magnetizing effects of currents upon needles. It created a great deal of excitement at the time, because it was the first clue which had been found to a relationship between electricity and magnetism.

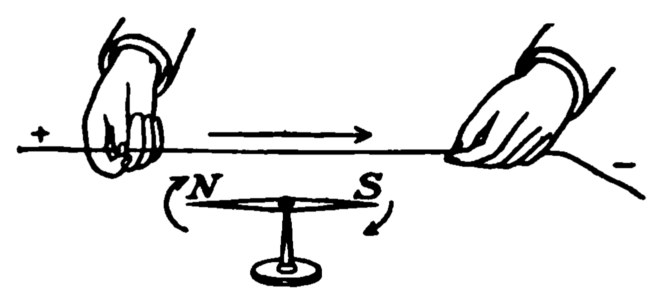


FIG. 243. Oersted's experiment

300. Plates of a galvanic cell are electrically charged. Since an electric current flows through a wire as soon as it is touched to the zinc and copper strips of a galvanic cell, we at once infer that the terminals of such a cell are electrically charged before they are connected. That this is indeed the case may be shown as follows:

Let a metal plate *A* (Fig. 244), covered with shellac on its lower side and provided with an insulating handle, be placed upon a similar plate *B* which is in contact with the knob of an electroscope. Let the copper plate of a galvanic cell be connected with *A* and the zinc plate with *B*, as in Fig. 244. Then let the connecting wires be removed and the plate *A* lifted away from *B*. The opposite electrical charges which were bound by their mutual attractions to the adjacent faces of *A* and *B*, so long as these faces were separated only by the thin coat of shellac, are freed as soon as *A* is lifted, and hence part of the charge on *B* passes to the leaves of the electroscope. These leaves will indeed be seen to diverge. If an ebonite rod which has been rubbed with flannel or cat's fur is brought near the electroscope, the leaves will diverge still farther, thus showing that the zinc plate of the galvanic cell is negatively charged.* If the experiment is repeated with the copper plate in contact with *B* and the zinc in contact with *A*, the leaves will be found to be positively charged.

* If the deflection of the gold leaves is too small for purposes of demonstration, let a battery of from five to ten cells be used instead of the single cell. If, however, the plates *A* and *B* are three or four inches in diameter, and if their surfaces are very flat, a single cell is sufficient.

HANS CHRISTIAN OERSTED
(1777–1851)

The discoverer of the connection between electricity and magnetism was a Dane and a professor at the University of Copenhagen. His famous experiment made in 1820 stimulated the researches which led to the modern industrial developments of electricity

JOSEPH HENRY (1797–1878)

Born in Albany, New York; taught physics and mathematics in Albany Academy and Princeton College. He invented the electromagnet (1828), discovered the oscillatory nature of the electric spark (1842) by magnetizing needles in the manner described on page 244, and made the first experiments in self-induction (1832). He was the first secretary of the Smithsonian Institution, and the organizer of the Weather Bureau

ELECTROMAGNETS

This page shows in the upper right-hand corner a photograph of the first electromagnet. It was constructed at Princeton in 1828 by Henry. He wound the arms of a U-shaped piece of iron with several layers of wire insulated by wrapping around it strips of silk. The main illustration is a huge modern lifting magnet which itself weighs 8720 pounds, is 5 feet 2 inches in diameter, and can lift a single flat piece of iron weighing 70,000 pounds. It has 118,000 ampere turns, and carries 84 amperes at 220 volts. The coil is built up of several pancakes of copper straps, the turns of strap being insulated from one another by asbestos ribbon wound between them. The magnet is loading a freight car with pig iron, of which its average lift is 4000 pounds

The terminals of a galvanic cell therefore carry positive and negative charges just as do the terminals of an electrical machine in operation. The + charge is always found upon the copper and the − charge upon the zinc. The source of these charges is the chemical action which takes place within the cell. When these terminals are connected by a conductor, a current flows through the latter just as in the case of the electrical machine; and it is the universal custom to consider that it flows from positive to negative (see § 293 and footnote), that is, from copper to zinc.

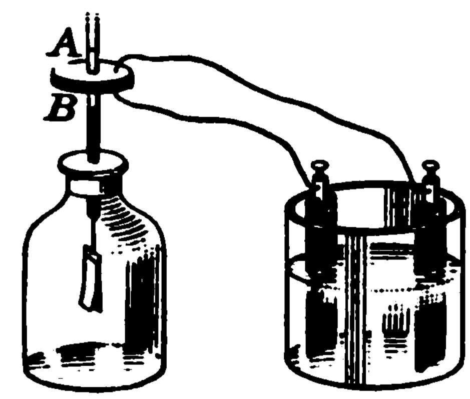


FIG. 244. Showing charges on plates of a voltaic cell

301. Comparison of a galvanic cell and a static machine. If one of the terminals of a galvanic cell is touched directly to the knob of a gold-leaf electroscope, without the use of the condenser plates *A* and *B* of Fig. 244, no divergence of the leaves will be detected; but if one knob of a static machine in operation were so touched, the leaves would probably be torn apart by the violence of the divergence. Since we have seen in § 294 that the divergence of the gold leaves is a measure of the potential of the body to which they are connected, we learn from this experiment that the chemical actions in the galvanic cell are able to produce between its terminals but a very small potential difference in comparison with that produced by the static machine between its terminals. As a matter of fact the potential difference between the terminals of the cell is about one volt, while that between the knobs of the electrical machine may be as much as 200,000 volts.

But if the knobs of the static machine are connected to the ends of the wire of Fig. 243, and the machine operated, the current sent through the wire will not be large enough to produce any appreciable effect upon the needle. Since under these same circumstances the galvanic cell produced a very large effect

upon the needle, we learn that although the cell develops a very small P. D. between its terminals, it nevertheless sends through the connecting wire very much more electricity per second than the static machine is able to send. This is because the chemical action of the cell is able to recharge the plates to their small P.D. practically as fast as they are discharged through the wire, whereas the static machine requires a relatively long time to recharge its terminals to their high P.D. after they have once been discharged.

QUESTIONS AND PROBLEMS

1. Under what conditions will an electric charge produce a magnetic effect?
2. How can you test whether or not a current is flowing in a wire?
3. How does the current delivered by a cell differ from that delivered by a static machine?
4. Mention three respects in which the behavior of magnets is similar to that of electric charges; two respects in which it is different.

Chemical Effects of the Current; Electrolysis *

302. Electrolysis. Let two platinum electrodes be dipped into a solution of dilute sulphuric acid, and let the terminals of a battery producing a pressure of 10 volts or more be applied to these *electrodes.* Oxygen gas is found to be given off at the electrode at which the current enters the solution, called the *anode,* while hydrogen is given off at the electrode at which the current leaves the solution, called the *cathode.* These gases may be collected in test tubes in the manner shown in Fig. 245.

In accordance with the theory now in vogue among physicists and chemists, when sulphuric acid is mixed with water so as to form a dilute solution, the H_2SO_4 molecules split up into three electrically charged parts, called *ions,* the two

* This subject should be accompanied or followed by a laboratory experiment on electrolysis and the principle of the storage battery. See, for example, Experiment 35 of the authors' Manual.

hydrogen ions each carrying a positive charge and the SO_4 ion a double negative charge (Fig. 246). This phenomenon is known as *dissociation*. The solution as a whole is neutral; that is, it is uncharged, because it contains just as many positive as negative charges.

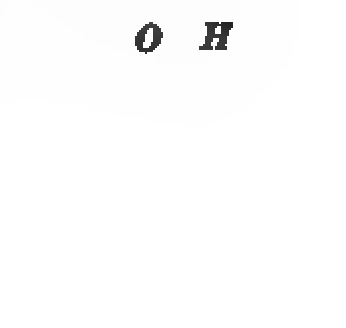


Fig. 245. Electrolysis of water

As soon as an electrical field is established in the solution by connecting the electrodes to the positive and negative terminals of a battery, the hydrogen ions begin to migrate toward the negative electrode (that is, the cathode) and there, after giving up their charges, unite to form molecules of hydrogen gas (Fig. 245). On the other hand, the negative SO_4 ions migrate to the positive electrode (that is, the anode), where they give up their charges to it, and then act upon the water (H_2O), thus forming H_2SO_4 and liberating oxygen.

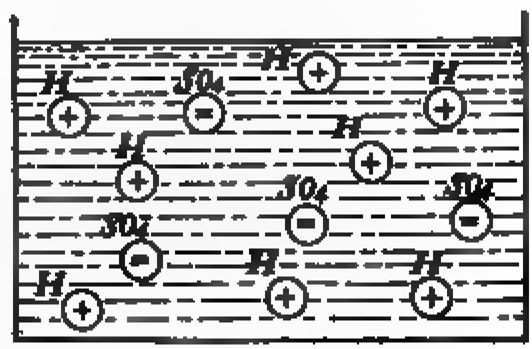


Fig. 246. Showing dissociation of sulphuric-acid molecules in water

If the volumes of hydrogen and of oxygen are measured, the hydrogen is found to occupy in every case just twice the volume occupied by the oxygen. This is, indeed, one of the reasons for believing that a molecule of water consists of two atoms of hydrogen and one of oxygen.

303. Electroplating. If the solution, instead of being sulphuric acid, had been one of copper sulphate ($CuSO_4$), the results would have been precisely the same in every respect, except that, since the hydrogen ions in the solution are now replaced by copper ions, the substance deposited on the cathode is pure copper instead of hydrogen. This is the principle involved in electroplating of all kinds. In commercial work the positive plate, that is, the plate at which the current

enters the bath, is always made from the same metal as that which is to be deposited from the solution, for in this case the SO_4 or other negative ions dissolve this plate as fast as the metal ions are deposited upon the other. The strength of the solution, therefore, remains unchanged. In effect, the metal is simply taken from one plate and deposited on the other. Fig. 247 represents a simple form of silver-plating bath. The anode *A* is of pure silver. The spoon to be plated is the cathode *K*. In practice the articles to be plated are often suspended from a central rod (Fig. 248), while on both sides about the articles are the suspended anodes. This arrangement gives a more even deposit of metal. In silver plating the solution consists of 500 grams of potassium cyanide and 250 grams of silver cyanide in 10 liters of water.

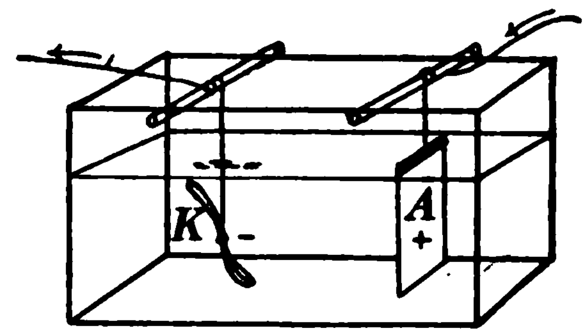


FIG. 247. A simple electroplating bath

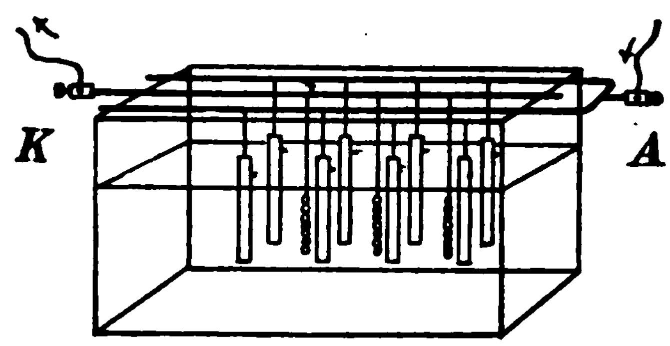


FIG. 248. Electroplating bath

304. Electrotyping. In the process of electrotyping, the page is first set up in the form of common type. A mold is then taken in wax or gutta-percha. This mold is then coated with powdered graphite to render it a conductor, after which it is ready to be suspended as the cathode in a copper-plating bath, the anode being a plate of pure copper and the liquid a solution of copper sulphate. When a sheet of copper as thick as a visiting card has been deposited on the mold, the latter is removed and the wax replaced by a type-metal backing, to give rigidity to the copper films. From such a plate as many as a hundred thousand impressions may be made. Nearly all books which run through large editions are printed from such electrotypes.

305. Legal units of current and quantity. In 1834 Faraday (see opposite p. 290) found that a given current of electricity flowing for a given time always deposits the same amount of a given element from a solution, whatever be the nature of the solution which contains the element. For example, one ampere, the unit of current, always deposits in an hour 4.025 grams of silver, whether the electrolyte is silver nitrate, silver cyanide, or any other silver compound. Similarly, an ampere will deposit in an hour 1.181 grams of copper, 1.203 grams of zinc, etc. Faraday further found that the amount of metal deposited in a given cell depended solely on the product of the current strength by the time, that is, on the *quantity* of electricity which had passed through the cell. These facts are made the basis of the legal definitions of current and quantity, thus:

The unit of quantity, called the coulomb, is the quantity of electricity required to deposit .001118 *gram of silver.*

The unit of current, the ampere, is the current which will deposit .001118 *gram of silver in one second.*

QUESTIONS AND PROBLEMS

1. What was the strength of a current that deposited 11.84 g. of copper in 30 min.?

2. How long will it take a current of 1 ampere to deposit 1 g. of silver from a solution of silver nitrate?

3. If the same current used in Problem 2 were led through a solution containing a zinc salt, how much zinc would be deposited in the same time?

4. How could a silver cup be given a gold lining by use of the electric current?

5. If the terminals of a battery are immersed in a glass of acidulated water, how can you tell from the rate of evolution of the gases at the two electrodes which is positive and which is negative?

6. The coulomb (§ 305) is 3 billion times as large as the electrostatic unit of quantity defined in § 280. How many electrons pass per second by a given point on a lamp filament which is carrying 1 ampere of current (see § 284)?

MAGNETIC EFFECTS OF THE CURRENT; PROPERTIES OF COILS

306. Shape of the magnetic field about a current. If we place the wire which connects the plates of a galvanic cell in a vertical position (Fig. 249) and explore with a compass needle the shape of the magnetic field about the current, we find that the magnetic lines are concentric circles lying in a plane perpendicular to the wire and having

FIG. 249 FIG. 250

Magnetic field about a current

the wire as their common center. We find, moreover, that reversing the current reverses the direction of the needle. If the current is very strong (say 40 amperes), this shape of the field can be shown by scattering iron filings on a plate through which the current passes (Fig. 249). If the current is weak, the experiment should be performed as indicated in Fig. 250.

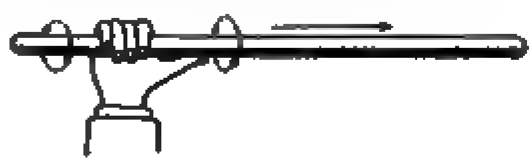


FIG. 251. The right-hand rule

The relation between the direction in which the current flows and the direction in which the N pole of the needle points (this is, by definition, the direction of the magnetic field) is given in the following convenient rule, known as Ampere's Rule: *If the right hand grasps the wire as in Fig. 251, so that the thumb points in the direction in which the current is flowing, then the magnetic lines encircle the wire in the same direction as do the fingers of the hand.*

307. Loop of wire carrying a current equivalent to a magnet disk. Let a single loop of wire be suspended from a thread in the manner shown in Fig. 252, so that its ends dip into two mercury cups. Then let the current from three or four dry cells be sent through the loop. The latter will be found to slowly set itself so that the face of the loop from which the magnetic lines emerge, as given by the right-hand rule (see § 306 and also Fig. 253), is toward the north. Let a bar magnet be brought near the loop. The latter will be found to behave toward the magnet in all respects as though it were a flat magnetic disk whose boundary is the wire, the face which turns toward the north being an N pole and the other an S pole.

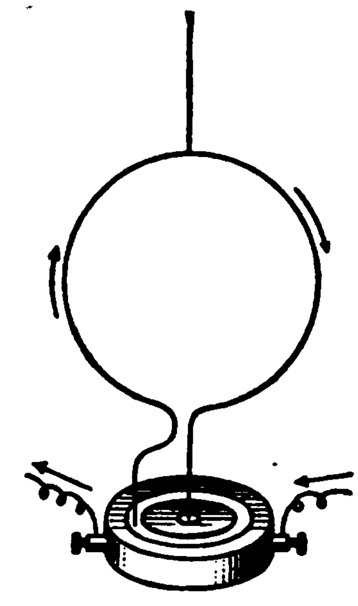


FIG. 252. A loop equivalent to a flat magnetic disk

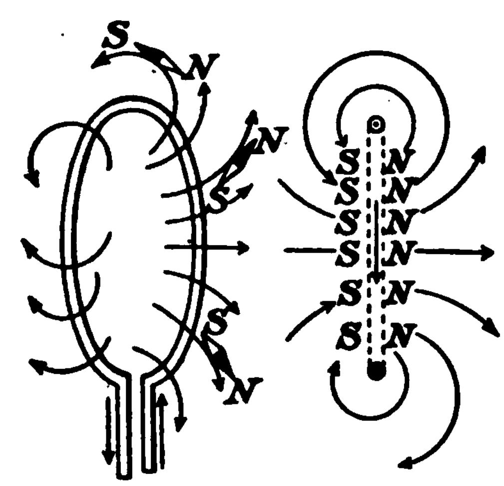


FIG. 253. North pole of disk is face from which magnetic lines emerge; south pole is face into which they enter

The experiment shows what position a loop bearing a current will always tend to assume in a magnetic field; for, since a magnet will always tend to set itself so that the line connecting its poles is parallel to the direction of the magnetic lines of the field in which it is placed, a loop must set itself so that a line connecting its magnetic poles is parallel to the lines of the magnetic field, that is, so that *the plane of the loop is perpendicular to the field* (see Fig. 254); or, to state the same thing in slightly different form, *if a loop of wire, free to turn, is carrying a current in a magnetic field, the loop will set itself so as to include as many as possible of the lines of force of the field.*

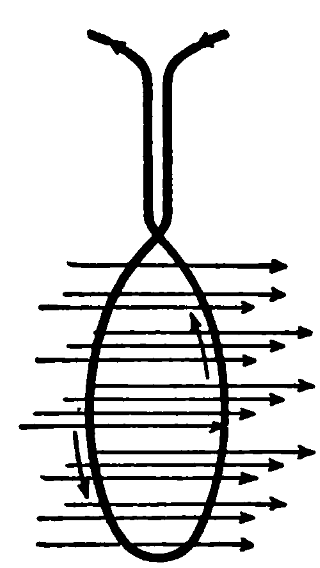


FIG. 254. Position assumed by a loop carrying a current in a magnetic field

308. Helix carrying a current equivalent to a bar magnet. Let a wire bearing a current be wound in the form of a helix and held near a suspended magnet, as in Fig. 255. It will be found to act in every respect like a magnet, with an N pole at one end and an S pole at the other.

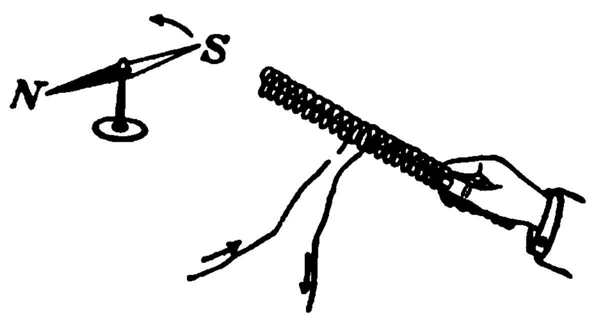


FIG. 255. Magnetic effect of a helix

This result might have been predicted from the fact that a single loop is equivalent to a flat-disk magnet; for when a series of such disks is placed side by side, as in the helix, the result must be the same as placing a series of disk magnets in a row, the N pole of one being directly in contact with the S pole of the next, etc. These poles would therefore all neutralize each other except at the two ends. We therefore get a magnetic field of the shape shown in Fig. 256, the direction of the arrows representing as usual the direction in which an N pole tends to move.

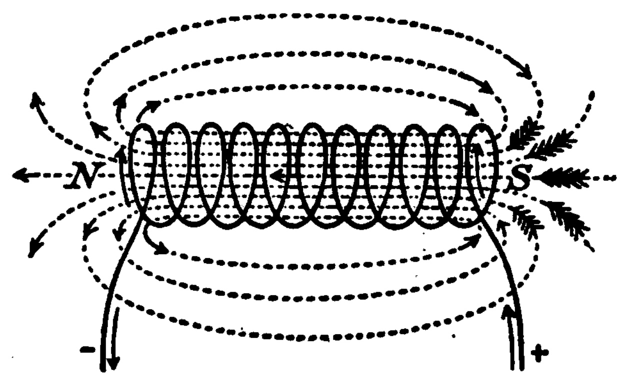


FIG. 256. Magnetic field of helix

The right-hand rule as given in § 306 is sufficient in every case to determine which is the N and which the S pole of a helix, that is, from which end the lines of magnetic force emerge from the helix and at which end they enter it. But it is found convenient, in the consideration of coils, to restate the right-hand rule in a slightly different way, thus: *If the coil is grasped in the right hand in such a way that the fingers point in the direction in which the current is flowing in the wires, the thumb will point in the direction of the north pole of the helix* (see Fig. 257). Similarly, if the sign of the poles is known, but the direction of the current unknown, it may

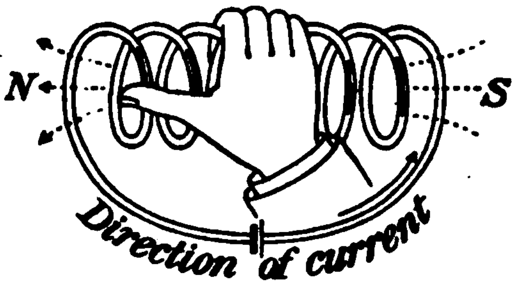


FIG. 257. Rule for poles of helix

be determined as follows: *If the right hand is placed against the coil with the thumb pointing in the direction of the lines of force* (that is, toward the north pole of the helix), *the fingers will pass around the coil in the direction in which the current is flowing.*

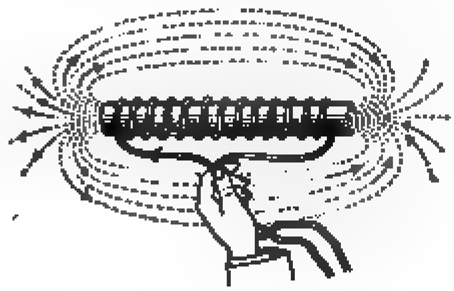


FIG. 258. The bar electromagnet

309. The electromagnet. Let a core of soft iron be inserted in the helix (Fig. 258). The poles will be found to be enormously stronger than before. This is because the core is magnetized by induction from the field of the helix in precisely the same way in which it would be magnetized by induction if placed in the field of a permanent magnet. The new field strength about the coil is now the sum of the fields due to the core and that due to the coil. If the current is broken, the core will at once lose the greater part of its magnetism. If the current is reversed, the polarity of the core will be reversed. Such a coil with a soft-iron core is called an *electromagnet.*

FIG. 259. The horseshoe electromagnet

The strength of an electromagnet can be very greatly increased by giving it such form that the magnetic lines can remain in iron throughout their entire length instead of emerging into air, as they do in Fig. 258. For this reason electromagnets are usually built in the horseshoe form and provided with an armature *A* (Fig. 259), through which a complete iron path for the lines of force is established, as shown in Fig. 260. The strength of such a magnet depends chiefly upon the number of *ampere turns* which encircle it, the expression "ampere turns" denoting the product of the number of turns of wire about the magnet by the number of amperes

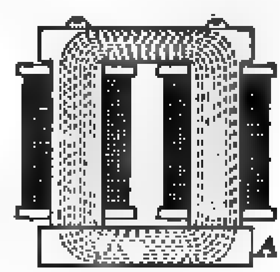


FIG. 260. The magnetic circuit of an electromagnet

flowing in each turn. Thus, a current of $\frac{1}{100}$ ampere flowing 1000 times around a core will make an electromagnet of precisely the same strength as a current of 1 ampere flowing 10 times about the core. (See modern lifting magnet opposite p. 247.)

QUESTIONS AND PROBLEMS

1. Describe the magnetic condition of the space about a trolley wire carrying a direct current.

2. In what direction will the north pole of a magnetic needle be deflected if it is held above a current flowing from north to south?

3. A man stands beneath a north-and-south trolley line and finds that a magnetic needle in his hand has its north pole deflected toward the east. What is the direction of the current flowing in the wire?

4. A loop of wire lying on the table carries a current which flows around it in a clockwise direction. Would a north magnetic pole at the center of the loop tend to move up or down?

5. If one looks down on the ends of a U-shaped electromagnet, does the current encircle the two coils in the same or in opposite directions? Does it run clockwise or counterclockwise about the N pole?

Measurement of Electric Currents

310. The galvanometer. Electric currents are, in general, measured by the strength of the magnetic effect which they are able to produce under specific conditions. Thus, if the wire carrying a current is wound into circular form, as in Fig. 261, the right-hand rule shows us that the shape of the magnetic field at the center of the coil is similar to that shown in the figure. If, then, the coil is placed in a north-and-south plane and a compass needle is

Fig. 261. Magnetic field about a circular coil carrying a current

André Marie Ampère (1775–1836)

French physicist and mathematician; son of one of the victims of the guillotine in 1793; professor at the Polytechnic School in Paris and later at the College of France; began his experiments on electromagnetism in 1820, very soon after Oersted's discovery; published his great memoir on the magnetic effects of currents in 1823; first stated the rule for the relation between the direction of a current in a wire and the direction of the magnetic field about it. The ampere, the practical unit of current, is named in his honor

HUGE ROTOR

The figure shows, in process of construction, one of the most recent types of huge generator of electricity, which are the outgrowth of the discovery of the relation between magnetism and electricity to which Ampère contributed so much. The figure shows in place two of the rotating electromagnets, which, as they swing past the huge coils of the stator surrounding them, at a peripheral speed of a mile and a half a minute, generate a current of 2700 amperes at 12,000 volts. This is one of the three 32,500-kilowatt machines built for installation at Niagara Falls

placed at the center, the passage of the current through the coil tends to deflect the needle so as to make it point east and west. The amount of deflection under these conditions is taken as the measure of current strength. The unit of current, the *ampere*, is in fact approximately the same as the current which, flowing through a circular coil of three turns and 10 centimeters radius, set in a north-and-south plane, will produce a deflection of 45 degrees at Washington in a small compass needle placed at its center. The legal definition of the ampere is, however, based on the chemical effect of a current. It was given in § 305.

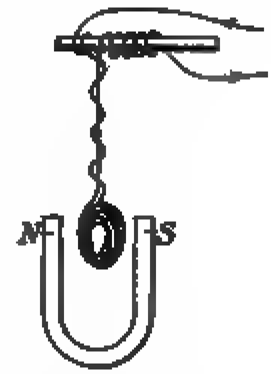


Fig. 262. Simple suspended-coil galvanometer

Nearly all current-measuring instruments consist essentially either of a small compass needle at the center of a fixed coil, as in Fig. 261, or of a movable coil suspended between the poles of a fixed magnet in the manner illustrated roughly in Fig. 262. The passage of the current through the coil produces a deflection, in the first case, of the magnetic needle with reference to the fixed coil, and, in the second case, of the coil with reference to the fixed magnet. If the instrument has been calibrated to give the strength of the current directly in amperes, it is called an *ammeter*; otherwise, a *galvanometer* (Fig. 263).

Fig. 263. A lecture-table galvanometer

311. The commercial ammeter. Fig. 264 shows the construction of the usual form of commercial ammeter. The coil c is pivoted on jewel bearings and is held at its zero

position by a spiral spring p. When a current flows through the instrument, if it were not for the spring p the coil would turn through about 120°, or until its N pole came opposite the S pole of the magnet (see Fig. 264). This zero position of the coil is chosen because it enables the scale divisions to be nearly equal. The conductor i, called a *shunt*, carries nearly all the current that enters the instrument at B, only an *exceedingly small* portion of it going through the moving coil c. The shunt is usually placed inside the instrument unless interchangeable shunts are desired.

FIG. 264. Construction of a commercial ammeter

QUESTIONS AND PROBLEMS

1. What is the principle involved in the chemical method of measuring the strength of an electric current? in the magnetic method?

2. How could you test whether or not the strength of an electric current is the same in all parts of a circuit? Try it.

3. Explain from the diagram of the commercial ammeter the principle of the suspended-coil, or d'Arsonval, type of galvanometer.

4. In calibrating an ammeter the current which produces a certain deflection is found to deposit $\frac{1}{2}$ g. of silver in 50 min. What is the strength of the current?

5. When a compass needle is placed, as in Fig. 261, at the middle of a coil of wire which lies in a north-and-south plane, the deflection produced in the needle by a current sent through the coil is approximately proportional to the strength of the current, provided the deflection is small, — not more, for example, than 20° or 25°; but when the deflection becomes large, — say 60° or 70°, — it increases very much more slowly than does the current which produces it. Can you see any reason why this should be so?

Electric Bell and Telegraph

312 The electric bell. The electric bell (Fig. 265) is one of the simplest applications of the electromagnet. When the button *P* is pressed (Figs. 265 and 266), the electric circuit of the battery is closed, and a current flows in at *A*, through the coils of the magnet, over the closed contact *c*, and out again at *B*. But as soon as this current is established, the electromagnet *E* pulls over the armature *a*, and in so doing breaks the contact at *c*. This stops the current and demagnetizes the magnet *E*. The armature is then thrown back against *c* by the elasticity of the spring *s* which supports it. No sooner is the contact made at *c* than the current again begins to flow and the former operation is repeated. Thus the circuit is automatically made and broken at *c*, and the hammer *H* is in consequence set into rapid vibration against the rim of the bell.

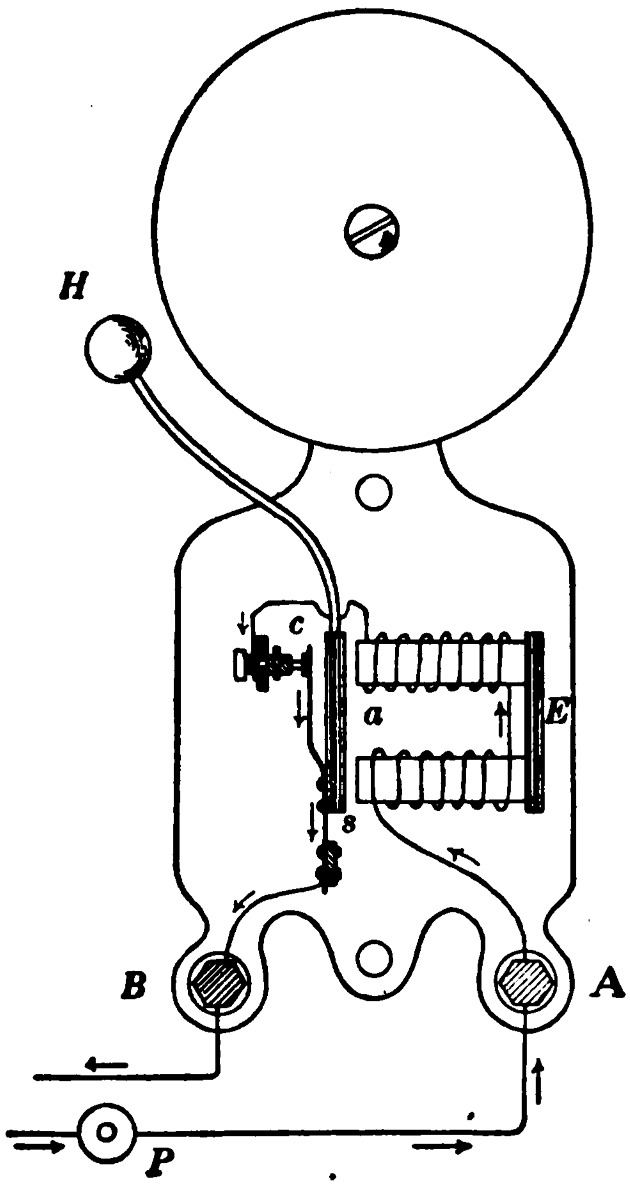


FIG. 265. The electric bell

313. The telegraph. The electric telegraph is another simple application of the electromagnet. The principle is illustrated in Fig. 267. As soon as the key *K*, at Chicago for example, is closed, the current flows over the line to, we will say, New York. There it passes through the electromagnet *m*, and thence back to Chicago through the earth. The armature *b* is held down by the electromagnet *m* as long as the key *K* is kept closed. As soon as the circuit is broken at *K* the armature is pulled up by the spring *d*. By means of a clockwork device the tape *c* is drawn along at a uniform rate beneath the pencil or pen carried

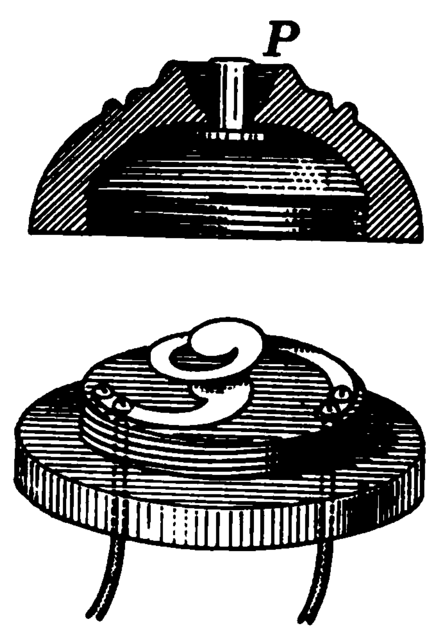


FIG. 266. Cross section of electric push button

by the armature *b*. A very short time of closing of *K* produces a dot upon the tape; a longer time, a dash. As the Morse, or telegraphic, alphabet consists of certain combinations of dots and dashes, any desired message may be sent from Chicago and recorded in New York. In modern

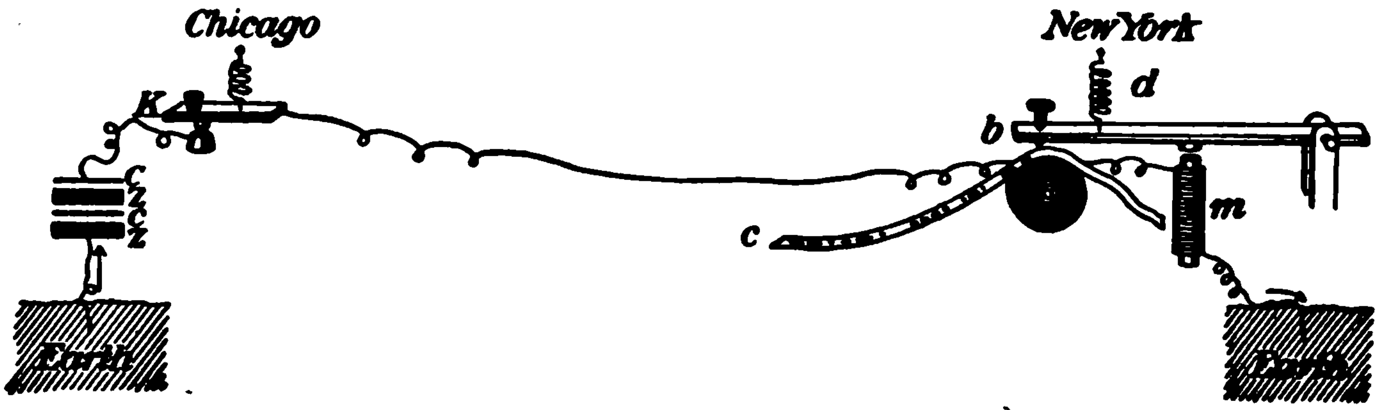


FIG. 267. Principle of the telegraph

practice the message is not ordinarily recorded on a tape, for operators have learned to read messages by ear, a very short interval between two clicks being interpreted as a dot, a longer interval as a dash.

The first commercial telegraph line was built by S. F. B. Morse (see on opposite page) between Baltimore and Washington. It was opened on May 24, 1844, with the now famous message, "What hath God wrought!"

314. The relay and sounder. Since the current that comes over a long telegraph line is of small amperage, the armature of the electromagnet of the receiving instrument must be made very light to respond to the action of the current. The electromagnet of this instrument is made of many thousand turns of fine wire, to secure the requisite number of ampere turns (§ 309) to work the armature. The clicks of such an armature are not sufficiently loud to be read easily by an operator. Hence at each station there is introduced a local circuit, which contains a local battery and a second and heavier electromagnet, which is called a sounder. The electromagnet on the main line is then called the relay (see Fig. 268 and the drawings opposite p. 261). The sounder has a very heavy armature

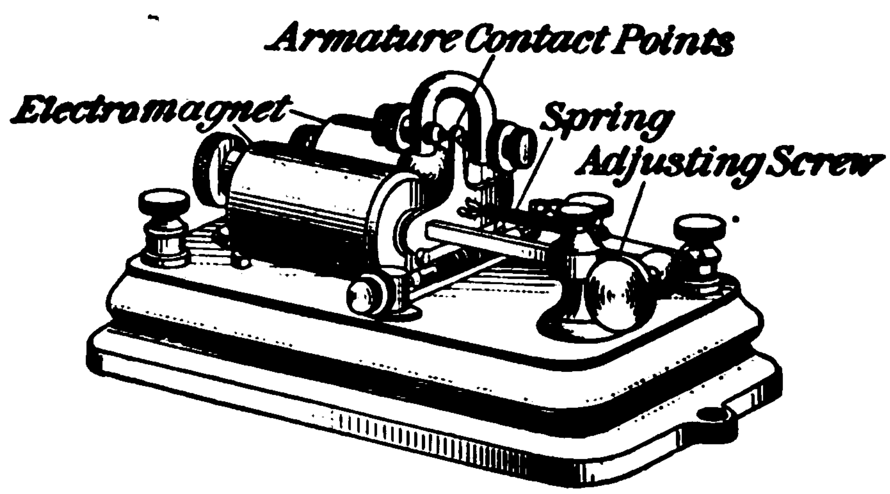
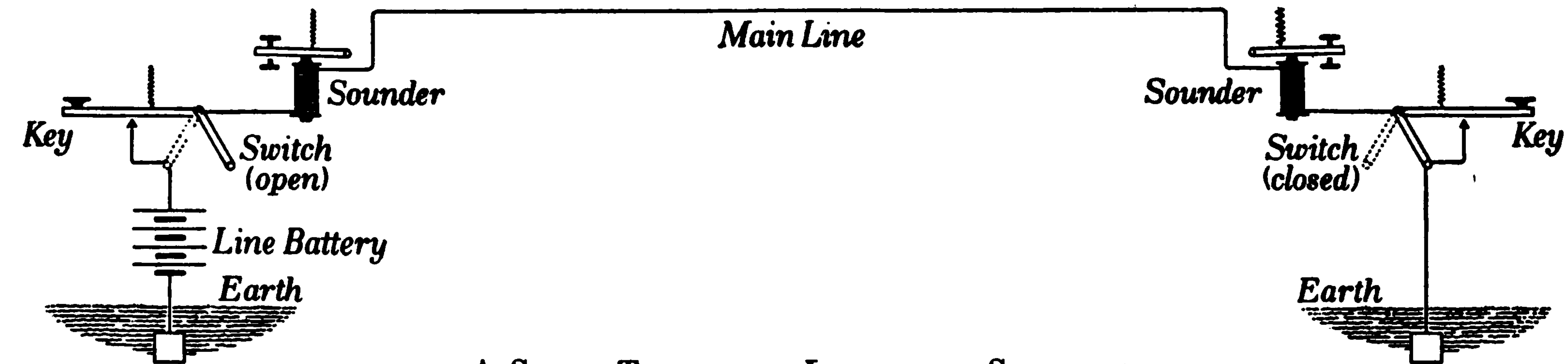


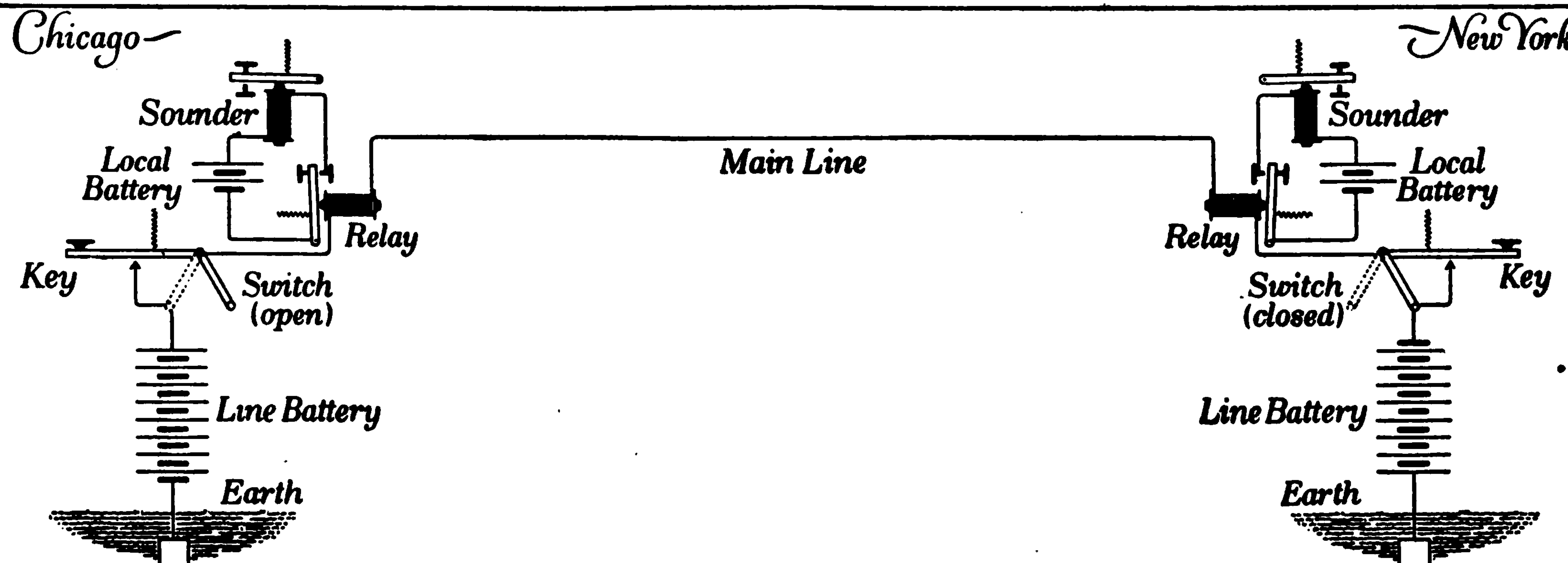
FIG. 268. The relay

Samuel F. B. Morse (1791-1872)

The inventor of the electromagnetic recording telegraph and of the dot-and-dash alphabet known by his name, was born at Charlestown, Massachusetts, graduated at Yale College in 1810, invented the commercial telegraph in 1832, and struggled for twelve years in great poverty to perfect it and secure its proper presentation to the public. The first public exhibition of the completed instrument was made in 1837 at New York University, signals being sent through 1700 feet of copper wire. It was with the aid of a $30,000 grant from Congress that the first commercial line was constructed in 1844 between Washington and Baltimore



A SHORT TELEGRAPH LINE USING SOUNDERS



A TELEGRAPH LINE USING RELAYS

(Fig. 269, A), which is so arranged that it clicks both when it is drawn down by its electromagnet against the stop S and when it is pushed up again by its spring, on breaking the current, against the stop t. The interval which elapses between these two clicks indicates to the operator whether a dot or a dash is sent. The small current in the main line simply serves to close and open the circuit in the local battery which operates the sounder (see drawings on opposite page). The electromagnets of the relay and the sounder differ in that the latter consists of a few hundred turns of coarse wire and carries a comparatively large current.

FIG. 269. The sounder

315. Plan of a telegraphic system. The actual arrangement of the various parts of a telegraphic system is shown in the drawings on the opposite page. When an operator at Chicago wishes to send a message to New York, he first opens the switch which is connected to his key, and which is always kept closed except when he is sending a message. He then begins to operate his key, thus controlling the clicks of both his own sounder and that at New York. When the Chicago switch is closed and the one at New York open, the New York operator is able to send a message back over the same line. In practice a message is not usually sent as far as from Chicago to New York over a single line, save in the case of transoceanic cables. Instead it is automatically transferred, say at Cleveland, to a second line, which carries it on to Buffalo, where it is again transferred to a third line, which carries it on to New York. The transfer is made in precisely the same way as the transfer from the main circuit to the sounder circuit. If, for example, the sounder circuit at Cleveland is lengthened so as to extend to Buffalo, and if the sounder itself is replaced by a relay (called in this case a repeater), and the local battery by a line battery, then the sounder circuit has been transformed into a repeater circuit, and all the conditions are met for an automatic transfer of the message at Cleveland.

QUESTIONS AND PROBLEMS

1. Draw a diagram showing how an electric bell works.

2. Draw a diagram of a short two-station telegraph line which has only one instrument at each station.

3. Draw a diagram showing how the relay and sounder operate in a telegraphic circuit. Why is a relay used?

Resistance and Electromotive Force

316. Electrical resistance.* Let the circuit of a galvanic cell be connected through a lecture-table ammeter, or any low-resistance galvanometer, and, for example, 20 feet of No. 30 copper wire, and let the deflection of the needle be noted. Then let the copper wire be replaced by an equal length of No. 30 German-silver wire. The deflection will be found to be a very small fraction of what it was at first.

A cell, therefore, which is capable of developing a certain fixed electrical pressure is able to force very much more current through a given wire of copper than through an exactly similar wire of German silver. We say, therefore, that German silver offers a higher *resistance* to the passage of electricity than does copper. Similarly, every particular substance has its own characteristic power of transmitting electrical currents. Since silver is the best conductor known, resistances of different substances are commonly referred to it as a standard, and the ratio between the resistance of a given wire of any substance and the resistance of an exactly similar silver wire is called the *specific resistance* of that substance. The specific resistances of some of the commoner metals in terms of silver are given below:

Silver . . .	1.00	Soft iron . .	6.00	German silver	18.1
Copper . . .	1.11	Platinum . .	7.20	Mercury . . .	63.1
Aluminium . .	1.87	Hard steel . .	13.5	Nichrome . .	66.6

The resistance of any conductor is directly proportional to its length and inversely proportional to the area of its cross section or to the square of its diameter.

The unit of resistance is the *ohm*, named after Georg Ohm (see opposite p. 268). A length of 9.35 feet of No. 30 copper

* This subject should be accompanied and followed by laboratory experiments on Ohm's law, on the comparison of wire resistances, and on the measurement of internal resistances. See, for example, Experiments 32, 33, and 34 of the authors' Manual.

wire, or 6.2 inches of No. 30 German-silver wire, has a resistance of about one ohm. *The legal definition of the ohm is a resistance equal to that of a column of mercury* 106.3 *centimeters long and* 1 *square millimeter in cross section, at* 0° *C.*

317. Resistance and temperature. Let the circuit of a galvanic cell be closed through a galvanometer of very low resistance and about 10 feet of No. 30 iron wire wrapped about a strip of asbestos. Let the deflection of the galvanometer be observed as the wire is heated in a Bunsen flame. As the temperature rises higher and higher the current will be found to fall continually.

The experiment shows that *the resistance of iron increases with rising temperature.* This is a general law which holds for all metals. In the case of liquid conductors, on the other hand, the resistance usually decreases with increasing temperature. Carbon and a few other solids show a similar behavior, the filament in the early form of incandescent electric lamp having only about half the resistance when hot which it has when cold.

318. Electromotive force and its measurement.* The potential difference which a galvanic cell or any other generator of electricity is able to maintain between its terminals when these terminals are not connected by a wire — that is, the total electrical pressure which the generator is capable of exerting — is commonly called its *electromotive force*, usually abbreviated to E.M.F. *The E.M.F. of an electrical generator may be defined as its capacity for producing electrical pressure, or P.D.* This P.D. might be measured, as in § 294, by the deflection produced in an electroscope when one terminal is connected to the case of the electroscope and the other terminal to the knob. Potential differences are, in fact, measured in this way in all so-called electrostatic voltmeters.

* This subject should be preceded or accompanied by laboratory work on E.M.F. See, for example, Experiment 31 of the authors' Manual.

The more common type of potential-difference measurer consists, however, of an instrument made like a galvanometer (Fig. 263), except that the coil of wire is made of very many turns of extremely fine wire, so that it carries a very small current. The amount of current which it does carry, however, is proportional to the difference in electrical pressure existing between its ends when these are touched to the two points whose P.D. is sought. The principle underlying this type of voltmeter will be better understood from a consideration of the following water analogy. If the stopcock *K* (Fig. 270) in the pipe connecting the water tanks *C* and *D* is closed, and if the water wheel *A* is set in motion by applying a weight *W*, the wheel will turn until it creates such a difference in the water levels between *C* and *D* that the back pressure against the left face of the wheel stops it and brings the weight *W* to rest. In precisely the same way the chemical action within the galvanic cell whose terminals are not joined (Fig. 271) develops positive and negative charges upon these terminals; that is, creates a P.D. between them until the back electrical pressure through the cell due to this P.D. is sufficient to put a stop to further chemical action. The seat of the E.M.F. is at the surfaces of contact of the metals with the acid, where the chemical actions take place.

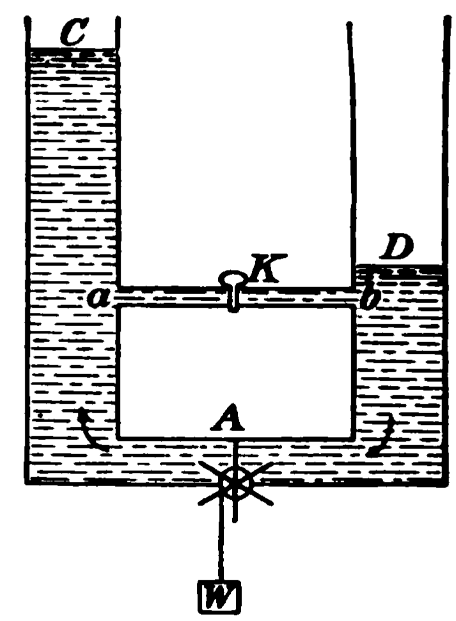


FIG. 270. Hydrostatic analogy of the action of a galvanic cell

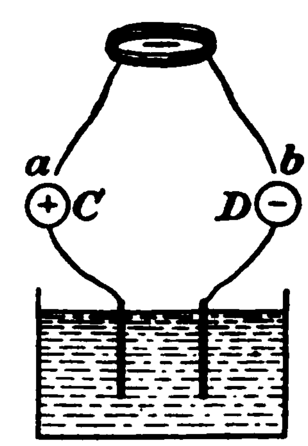


FIG. 271. Measurement of P.D. between the terminals of a galvanic cell

Now, if the water reservoirs (Fig. 270) are put in communication by opening the stopcock *K*, the difference in level between *C* and *D* will begin to fall, and the wheel will begin to build it up again. But if the carrying

capacity of the pipe *ab* is small in comparison with the capacity of the wheel to remove water from *D* and supply it to *C*, then the difference of level which permanently exists between *C* and *D* when *K* is open will not be appreciably smaller than when it is closed. In this case the current which flows through *ab* may obviously be taken as a measure of the difference in pressure which the pump is able to maintain between *C* and *D* when *K* is closed.

In precisely the same way, if the terminals *C* and *D* of the cell (Fig. 271) are connected by attaching to them the terminals *a* and *b* of any conductor, they at once begin to discharge through this conductor, and their P.D. therefore begins to fall. But if the chemical action in the cell is able to recharge *C* and *D* very rapidly in comparison with the ability of the wire to discharge them, then the P.D. between *C* and *D* will not be appreciably lowered by the presence of the connecting conductor. In this case the current which flows through the conducting coil, and therefore the deflection of the needle at its center, may be taken as a measure of the electrical pressure developed by the cell, that is, of the P.D. between its unconnected terminals.

FIG. 272. Lecture-table voltmeter

The common voltmeter (Fig. 272) is, then, exactly like an ammeter, save that it offers so high a resistance to the passage of electricity through it that it does not appreciably reduce the P.D. between the points to which it is connected.

319. The commercial voltmeter. Fig. 273 shows the construction of the common form of commercial voltmeter. It differs from the ammeter (Fig. 264) in that the shunt is omitted, and a high-resistance coil *R* is put in series with the moving coil *c*. The resistance of a voltmeter may be many thousand ohms. The current that passes through it is very small.

320. The electromotive forces of galvanic cells. Let a voltmeter of any sort be connected to the terminals of a simple galvanic cell, like that of Fig. 242. Then let the distance between the plates and the amount of their immersion be changed through wide limits. It will be found that the deflection produced is altogether independent of the shape or size of the plates or their distance apart. But if the nature of the plates is changed, the deflection changes. Thus, while copper and zinc in dilute sulphuric acid have an E.M.F. of one volt, carbon and zinc show an E.M.F. of at least 1.5 volts, while carbon and copper will show an E.M.F. of very much less than a volt. Similarly, by changing the nature of the liquid in which the plates are immersed, we can produce changes in the deflection of the voltmeter.*

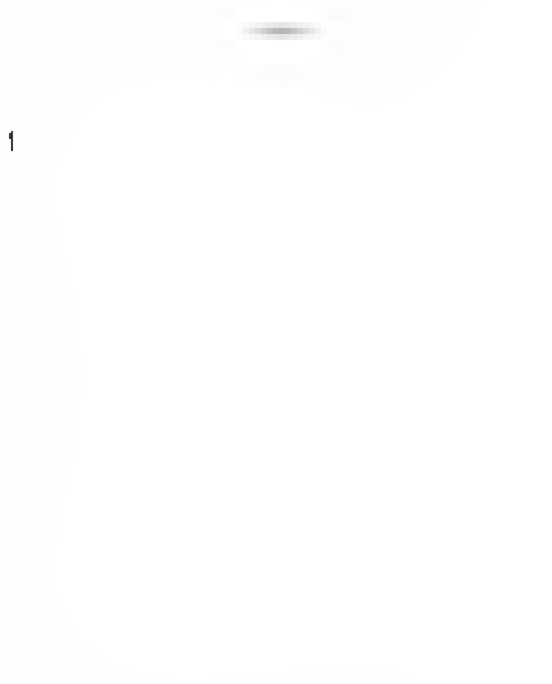


FIG. 273. Principle of commercial voltmeter

We learn, therefore, that *the E.M.F. of a galvanic cell depends simply upon the materials of which the cell is composed, and not at all upon the shape, size, or distance apart of the plates.*

321. Fall of potential along a conductor carrying a current. Not only does a P.D. exist between the terminals of a cell on open circuit, but also between any two points on a conductor through which a current is passing. For example, in the electrical circuit shown in Fig. 274 the potential at the point *a* is higher than that at *m*, that at *m* higher than that at *n*, etc., just as, in the water circuit shown in Fig. 275, the

* A vertical lecture-table voltmeter (Fig. 272) and a similar ammeter are desirable for this and some of the following experiments, but homemade high- and low-resistance galvanometers, like those described in the authors' Manual, are thoroughly satisfactory, save for the fact that one student must take the readings for the class.

hydrostatic pressure at a is greater than that at m, that at m greater than that at n, etc. The fall in the water pressure between m and n (Fig. 275) is measured by the water head $n's$. If we wish to measure the fall in electrical potential between m and n (Fig. 274), we touch the terminals of a voltmeter to these points in the manner shown in the figure. Its reading gives us at once the P.D. between m and n in volts, provided always that its own current-carrying capacity is so small that it does not appreciably lower the P.D. between the points m and n by being touched across them; that is, provided the current which flows through it is negligible in comparison with that which flows through the conductor which already joins the points m and n.

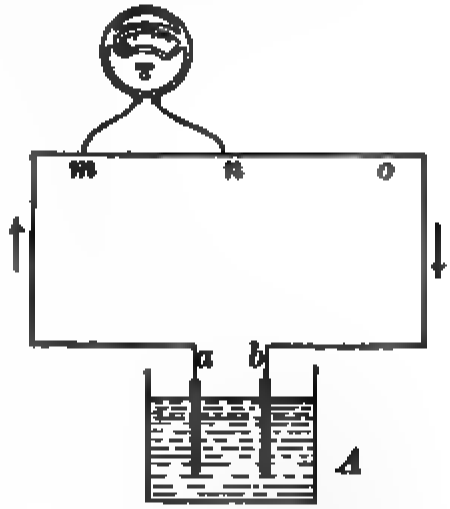


FIG. 274. Showing method of connecting voltmeter to find P.D. between any two points m and n on an electrical circuit

322. Ohm's law. In 1826 Ohm announced the discovery that *the currents furnished by different galvanic cells, or combinations of cells, are always directly proportional to the E.M.F.'s existing in the circuits in which the currents flow, and inversely proportional to the total resistances of these circuits*; that is, if I represents the current in amperes, E the E.M.F. in volts, and R the resistance of the circuit in ohms, then Ohm's law as applied to the complete circuit is

FIG. 275. Hydrostatic analogy of fall of potential in an electrical circuit

$$I = \frac{E}{R}; \text{ that is, current} = \frac{\text{electromotive force}}{\text{resistance}}. \tag{1}$$

As applied to any portion of an electrical circuit, Ohm's law is

$$I = \frac{P.D.}{R}; \text{ that is, current} = \frac{\text{potential difference}}{\text{resistance}}, \quad (2)$$

where P.D. represents the difference of potential in volts between any two points in the circuit, and R the resistance in ohms of the conductor connecting these two points. This is one of the most important laws in physics.

Both of the above statements of Ohm's law are included in the equation

$$\text{amperes} = \frac{\text{volts}}{\text{ohms}}. \quad (3)$$

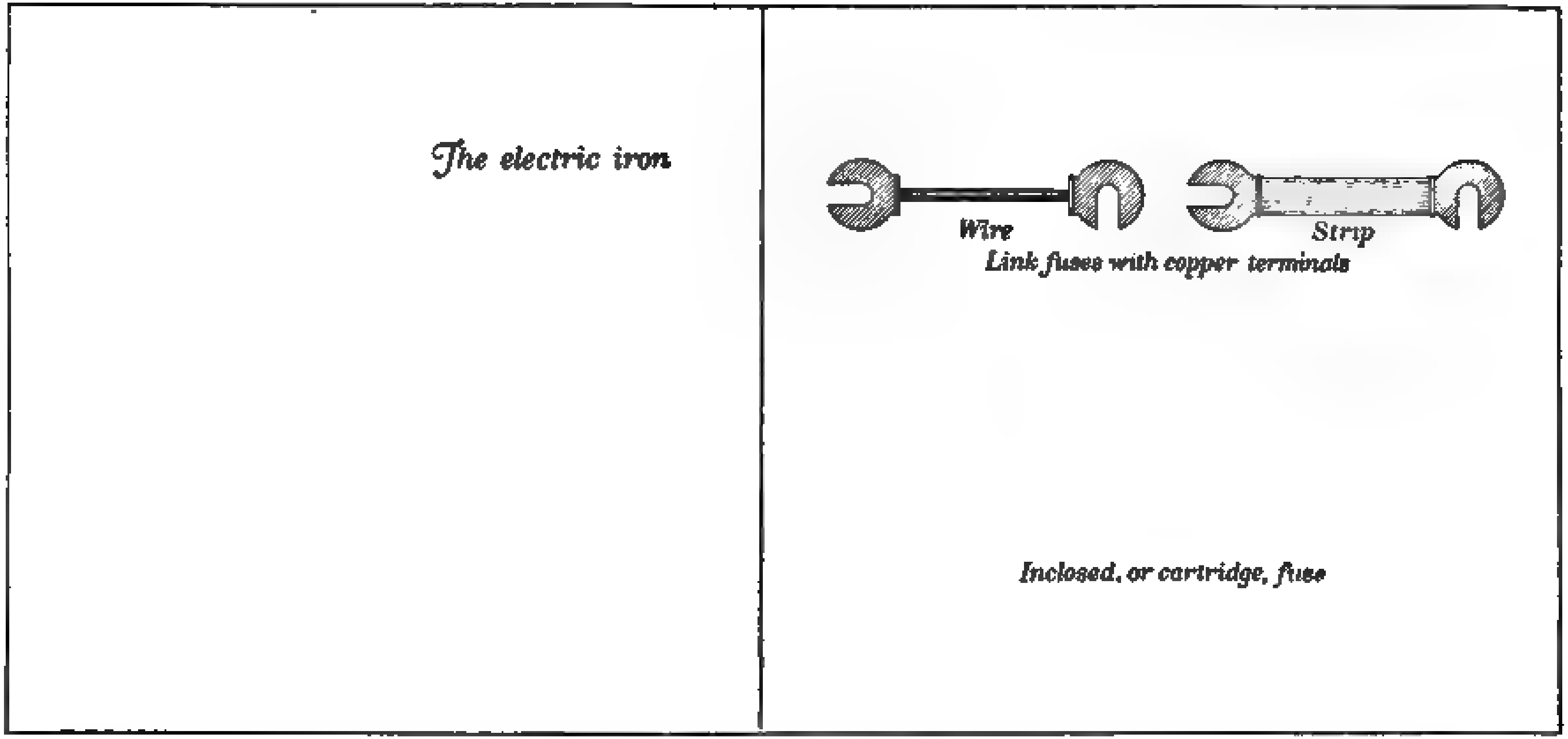
323. Internal resistance of a galvanic cell. Let the zinc and copper plates of a simple galvanic cell be connected to an ammeter, and the distance between the plates then increased. The deflection of the needle will be found to decrease, or if the amount of immersion is decreased, the current also will decrease.

Now, since the E.M.F. of a cell was shown in § 320 to be wholly independent of the area of the plates immersed or of the distance between them, it will be seen from Ohm's law that the change in the current in these cases must be due to some change in the total resistance of the circuit. Since the wire which constitutes the outside portion of the circuit has remained the same, we must conclude that *the liquid within the cell, as well as the external wire, offers resistance to the passage of the current.* This internal resistance of the liquid is directly proportional to the distance between the plates, and inversely proportional to the area of the immersed portion of the plates. If, then, we represent the external resistance of the circuit of a galvanic cell by R_e and the internal by R_i, Ohm's law as applied to the entire circuit takes the form

$$I = \frac{E}{R_e + R_i}. \quad (4)$$

Georg Simon Ohm (1787–1854)

German physicist and discoverer of the famous law in physics which bears his name. He was born and educated at Erlangen. It was in 1826, while he was teaching mathematics at a gymnasium in Cologne, that he published his famous paper on the experimental proof of his law. At the time of his death he was professor of experimental physics in the university at Munich. The ohm, the practical unit of resistance, is named in his honor



THE ELECTRIC IRON AND FUSES

The heating effect of the current is made use of in appliances like electric stoves, toasters, soldering irons, water heaters, and laundry irons. The heating element of an electric iron usually consists of nickel-chromium (" nichrome ") ribbon wound upon a sheet of mica. An ordinary electric iron requires about 600 watts, or enough power to operate twenty-four 25-watt lamps. The electric fuses shown above are the *link* type and the *inclosed* type. Fuses are used as part of the electric circuit to prevent damage to lamps, motors, telephones, etc. when excessive current flows on account of short circuits or other causes. To prevent the scattering of red-hot molten metal when a fuse blows out, the inclosed form is generally used. If *F* blows out, the current melts *s*, and the consequent blackening of the paper label covering it shows that the fuse is gone

Thus, if a simple cell has an internal resistance of 2 ohms and an E.M.F. of 1 volt, the current which will flow through the circuit when its terminals are connected by 9.35 ft. of No. 30 copper wire (1 ohm) is $\frac{1}{1+2} = .33$ ampere.

324. Measurement of internal resistance. A simple and direct method of finding a length of wire which has a resistance equivalent to the internal resistance of a cell is to connect the cell first to an ammeter or any galvanometer of negligible resistance* and then to introduce enough German-silver wire into the circuit to reduce the galvanometer reading to half its original value. The internal resistance of the cell is then equal to that of the German-silver wire. Why? A still easier method in case both an ammeter and a voltmeter are available is to divide the E.M.F. of the cell as given by the voltmeter by the current which the cell is able to send through the ammeter when connected directly to its terminals; for in this case R_e of equation (4) is negligibly small; therefore $R_i = \frac{E}{I}$. This gives the internal resistance directly in ohms.

325. Measurement of any resistance by ammeter-voltmeter method. The simplest way of measuring the resistance of a wire, or, in general, of any conductor, is to connect it into the circuit of a galvanic cell in the manner shown in Fig. 276. The ammeter A is inserted to measure the current, and the voltmeter V to measure the P.D. between the ends a and b of the wire r, the resistance of which is sought. The resistance of r in ohms is obtained at once from the ammeter and voltmeter readings with the aid of the law $I = \frac{\text{P.D.}}{R}$, from which it follows that $R = \frac{\text{P.D.}}{I}$. Thus, if the voltmeter indicates a P.D. of .4 volt and the ammeter a current of .5 ampere, the resistance of r is $\frac{.4}{.5} = .8$ ohm.†

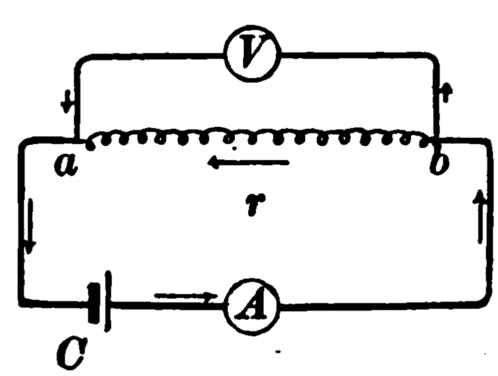


FIG. 276. Ammeter-voltmeter method of measuring resistance

* A lecture-table ammeter is best, but see note on page 266.

† See Experiment 33 of the authors' Manual for Wheatstone's bridge method.

326. Joint resistance of conductors connected in series and in parallel. When resistances are connected as in Fig. 277, so that the same current flows through each of them in succession, they are said to be connected *in series*. The total resistance of a number of conductors so connected is the sum of the several resistances. Thus, in the case shown in the figure the total resistance between *a* and *b* is 10 ohms.

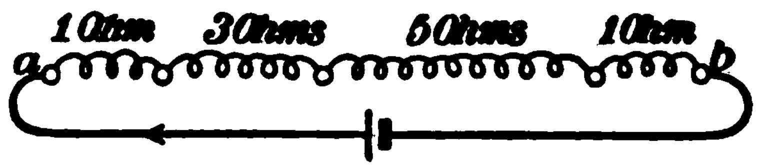


FIG. 277. Series connections

When *n* exactly similar conductors are joined in the manner shown in Fig. 278, that is, *in parallel or multiple*, the total resistance between *a* and *b* is $1/n$ of the resistance of one of them; for obviously, with a given P.D. between the points *a* and *b*, four conductors will carry four times as much current as one, and *n* conductors will carry *n* times as much current as one. Therefore the resistance, which is inversely proportional to the carrying capacity (see § 322), is $1/n$ as much as that of one.

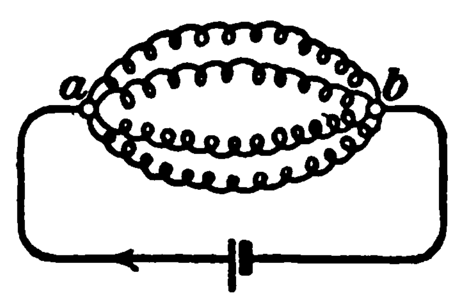


FIG. 278. Parallel connections

327. Shunts. A wire connected in parallel with another wire is said to be a *shunt* to that wire. Thus, the conductor X (Fig. 279) is said to be shunted across the resistance R. Under such conditions the currents carried by R and X will be inversely proportional to their resistances, so that if X is 1 ohm and R is 10 ohms, R will carry $\frac{1}{10}$ as much current as X, or $\frac{1}{11}$ of the whole current. In other words, since the carrying power, or *conductance*, of X is ten times that of R, ten times as much current will flow through X as through R, or $\frac{10}{11}$ of the whole current will pass through the shunt. The ammeter (Fig. 264) uses a shunt of exceedingly small resistance.

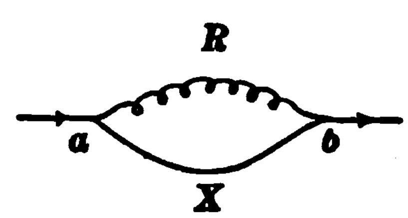


FIG. 279. A shunt

QUESTIONS AND PROBLEMS

1. How can you prove that the E.M.F. of a cell does not depend upon the size or nearness of the plates?

2. How can you prove that the internal resistance of a cell becomes smaller when the plates are made larger? when placed closer together?

3. If the potential difference between the terminals of a cell on open circuit is to be measured by means of a galvanometer, why must the galvanometer have a high resistance?

4. Why are iron wires used on telegraph lines but copper wires on trolley systems?

5. A voltmeter which has a resistance of 2000 ohms is shunted across the terminals A and B of a wire which has a resistance of 1 ohm. What fraction of the total current flowing from A to B will be carried by the voltmeter?

6. In a given circuit the P.D. across the terminals of a resistance of 19 ohms is found to be 3 volts. What is the P.D. across the terminals of a 3-ohm wire in the same circuit?

7. The resistance of a certain piece of German-silver wire is 1 ohm. What will be the resistance of another piece of the same length but of twice the diameter?

8. How much current will flow between two points whose P.D. is 2 volts, if they are connected by a wire having a resistance of 12 ohms?

9. What P.D. exists between the ends of a wire whose resistance is 100 ohms when the wire is carrying a current of .3 ampere?

10. If a voltmeter attached across the terminals of an incandescent lamp shows a P.D. of 110 volts, while an ammeter connected in series with the lamp indicates a current of .5 ampere, what is the resistance of the incandescent filament?

11. A certain storage cell having an E.M.F. of 2 volts is found to furnish a current of 20 amperes through an ammeter whose resistance is .05 ohm. Find the internal resistance of the cell.

12. The E.M.F. of a certain battery is 10 volts and the strength of the current obtained through an external resistance of 4 ohms is 1.25 amperes. What is the internal resistance of the battery?

13. Consider the diameter of No. 20 wire to be three times that of No. 30. A certain No. 30 wire 1 meter long has a resistance of 6 ohms. What would be the resistance of 4 meters of No. 20 wire made of the same metal?

14. Three wires, each having a resistance of 15 ohms, were joined in parallel and a current of 3 amperes sent through them. How much was the E.M.F. of the current?

Primary Cells

328. Study of the action of a simple cell. If the simple cell already described, that is, zinc and copper strips in dilute sulphuric acid, is carefully observed, it will be seen that, so long as the plates are not connected by a conductor, fine bubbles of gas are slowly formed at the zinc plate, but none at the copper plate. As soon, however, as the two strips are put into metallic connection, bubbles appear in great numbers about the copper plate (Fig. 280), and at the same time a current manifests itself in the connecting wire. These are bubbles of hydrogen. Their appearance on the zinc may be prevented either by using a plate of chemically pure zinc or by amalgamating impure zinc, that is, by coating it over with a thin film of mercury. But the bubbles on the copper cannot be thus disposed of. They are an invariable accompaniment of the current in the circuit. If the current is allowed to run for a considerable time, it will be found that the zinc wastes away, even though it has been amalgamated, but that the copper plate does not undergo any change.

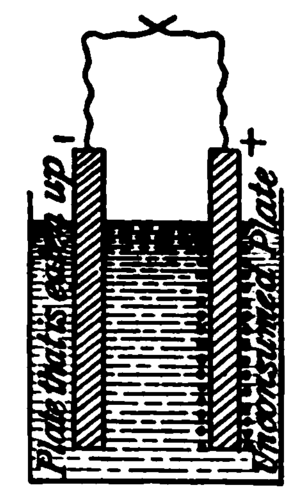


Fig. 280. Chemical actions in the voltaic cell

We learn, therefore, that the electrical current in the simple cell is accompanied by the eating up of the zinc plate by the liquid, and by the evolution of hydrogen bubbles at the copper plate. In every type of galvanic cell, actions similar to these two are always found; that is, *one of the plates is always eaten up, and upon the other plate some element is deposited.* The zinc, which is eaten, is the one which we found to be negatively charged when tested (§ 300), so that when the terminals are connected through a wire, the negative electrons flow through this wire from the zinc plate to the copper plate. This means, in accordance with the convention mentioned in the footnote to § 293, that *the direction of the current through the external circuit is always from the uneaten to the eaten plate.*

329. Local action and amalgamation. The cause of the appearance of the hydrogen bubbles at the surface of impure zinc when dipped in dilute sulphuric acid is that little

electrical circuits are set up between the zinc and the small impurities in it (carbon or iron particles) in the manner indicated in Fig. 281. If the zinc is pure, these little local currents cannot, of course, be set up, and consequently no hydrogen bubbles appear. Amalgamation stops this so-called *local action*, because the mercury dissolves the zinc, while it does not dissolve the carbon, iron, or other impurities. The zinc-mercury amalgam formed is a homogeneous substance which spreads over the whole surface and covers up the impurities. It is important, therefore, to amalgamate the zinc in a battery, in order to prevent the consumption of the zinc when the cell is on open circuit. The zinc is under all circumstances eaten up when the current is flowing, amalgamation serving only to prevent its consumption when the circuit is open.

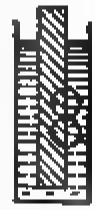


FIG. 281. Local action

330. Theory of the action of a simple cell. A simple cell may be made of any two dissimilar metals immersed in a solution of any acid or salt. For simplicity let us examine the action of a cell composed of plates of zinc and copper immersed in a dilute solution of hydrochloric acid. The chemical formula for hydrochloric acid is HCl. This means that each molecule of the acid consists of one atom of hydrogen combined with one atom of chlorine. As was explained under electrolysis (§ 302), the acid dissociates into positively and negatively charged ions (Fig. 282).

FIG. 282. Showing dissociation of hydrochloric-acid molecules in water

When a zinc plate is placed in such a solution, the acid attacks it and pulls zinc atoms into solution. Now, whenever a metal dissolves in an acid, its atoms, for some unknown reason, go into solution bearing little positive charges. *The corresponding negative charges must be left on the zinc plate* in precisely the same way in which a negative charge is left on silk when positive electrification is produced on a glass rod by rubbing it with the silk. It is in this way, then, that we account for the negative

charge which we found upon the zinc plate in the experiment which was performed with the galvanic cell and the electroscope (see § 300).

The passage of positively charged zinc ions into solution gives a positive charge to the solution about the zinc plate, so that the hydrogen ions tend to be repelled away from this plate. When these repelled hydrogen ions reach the copper plate, some of them give up their charges to it and then collect as bubbles of hydrogen gas. It is in this way that we account for the positive charge which we found on the copper plate in the experiment of § 300.

If the zinc and copper plates are not connected by an outside conductor, this passage of positively charged zinc ions into solution continues but a very short time, for the zinc soon becomes so strongly charged negatively that it pulls back on the + zinc ions with as much force as the acid is pulling them into solution. In precisely the same way the copper plate soon ceases to take up any more positive electricity from the hydrogen ions, since it soon acquires a large enough + charge to repel them from itself with a force equal to that with which they are being driven out of solution by the positively charged zinc ions. It is in this way that we account for the fact that on open circuit no chemical action goes on in the simple galvanic cell, the zinc and copper plates simply becoming charged to a definite difference of potential which is called the E.M.F. of the cell.

When, however, the copper and zinc plates are connected by a wire, a current at once flows from the copper to the zinc, and the plates thus begin to lose their charges. This allows the acid to pull more zinc into solution at the zinc plate, and allows more hydrogen to go out of solution at the copper plate. These processes, therefore, go on continuously so long as the plates are connected. Hence a continuous current flows through the connecting wire until the zinc is all eaten up or the hydrogen ions have all been driven out of the solution, that is, until either the plate or the acid has become exhausted.

331. Polarization. If the simple galvanic cell described is connected to a lecture-table ammeter through two or three feet of No. 30 German-silver wire, the deflection of the needle will decrease slowly; but if the hydrogen is removed from the copper plate (this can be done completely only by removing and thoroughly drying the plate), the deflection will be found to return to its first value.

The experiment shows clearly that the observed falling off in current was due to the collection of hydrogen about the

copper plate. This phenomenon of the weakening of the current from a galvanic cell is called the *polarization* of the cell.

332. Causes of polarization. The presence of the hydrogen bubbles on the positive plate causes a diminution in the strength of the current for two reasons: first, since hydrogen is a nonconductor, by collecting on the plate it diminishes the effective area of the plate and therefore increases the internal resistance of the cell; second, the collection of the hydrogen about the copper plate lowers the E.M.F. of the cell, because it virtually substitutes a hydrogen plate for the copper plate, and we have already seen (§ 320) that a change in any of the materials of which a cell is composed changes its E.M.F. That there is a real fall in E.M.F. as well as a rise in internal resistance when a cell polarizes may be directly proved in the following way:

Let the deflection of a lecture-table voltmeter whose terminals are attached to the freshly cleaned plates of a simple cell be noted. Then let the cell's terminals be short-circuited through a coarse wire for half a minute. As soon as the wire is removed, the E.M.F., indicated by the voltmeter, will be found to be much lower than at first. It will, however, gradually creep back toward its old value as the hydrogen disappears from the plate, but a thorough cleaning and drying of the plate will be necessary to restore completely the original E.M.F.

The different forms of galvanic cells in common use differ chiefly in different devices employed either for disposing of the hydrogen bubbles or for preventing their formation. The most common types of such cells are described in the following sections.

333. The Daniell cell. The Daniell cell consists of a zinc plate immersed in zinc sulphate and a copper plate immersed in copper sulphate, the two liquids being kept apart either by means of an unglazed earthen cup, as in the type shown in Fig. 283,* or else by gravity.

* To set up, fill the battery jar with a saturated solution of copper sulphate. Fill the porous cup with water and add a handful of zinc sulphate crystals.

In this cell polarization is almost entirely avoided, for the reason that no opportunity is given for the formation of hydrogen bubbles; for, just as the hydrochloric acid solution described in § 330 consists of positive hydrogen ions and negative chlorine ions in water, so the zinc sulphate ($ZnSO_4$) solution consists of positive zinc ions and negative SO_4 ions, and the copper sulphate solution of positive copper ions and negative SO_4 ions. Now the zinc of the zinc plate goes into solution in the zinc sulphate in precisely the same way that it goes into solution in the hydrochloric acid of the simple cell described in § 330. This gives a positive charge to the solution about the zinc plate, and causes a movement of the positive ions between the two plates from the zinc toward the copper, and of negative ions in the opposite direction, both the Zn and the SO_4 ions being able to pass through the porous cup. Since the positive ions about the copper plate consist of atoms of copper, it will be seen that the material which is driven out of solution at the copper plate, instead of being hydrogen, as in the simple cell, is metallic copper. Since, then, the element which is deposited on the copper plate is the same as that of which it already consists, it is clear that neither the E.M.F. nor the resistance of the cell can be changed because of this deposit; that is, the cause of the polarization of the simple cell has been removed.

FIG. 283. The Daniell cell

The great advantage of the Daniell cell lies in the relatively high degree of constancy in its E.M.F. (1.08 volts). It has a comparatively high internal resistance (one to six ohms) and is therefore incapable of producing very large currents, — about one ampere at most. It will furnish a very constant current, however, for a great length of time, in fact, until all of the copper is driven out of the copper sulphate solution. In order to keep a constant supply of the copper ions in the solution, copper-sulphate crystals are kept in the compartment S of the cell of Fig. 283 or in the bottom of the gravity cell. These dissolve as fast as the solution loses its strength through the deposition of copper on the copper plate.

The Daniell is a so-called "closed-circuit" cell; that is, its circuit should be left closed (through a resistance of thirty or forty ohms)

whenever the cell is not in use. If it is left on open circuit, the copper sulphate diffuses through the porous cup, and a brownish muddy deposit of copper or copper oxide is formed upon the zinc. Pure copper is also deposited in the pores of the porous cup. Both of these actions damage the cell. When the circuit is closed, however, since the electrical forces always keep the copper ions moving toward the copper plate, these damaging effects are to a large extent avoided.

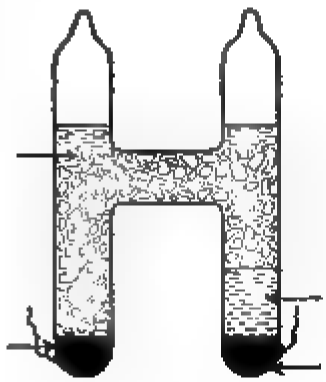


Fig. 284. The Weston normal cell

334. The Weston normal cell; the volt. This cell consists of a positive electrode of mercury in a paste of mercurous sulphate, and a negative electrode of cadmium amalgam in a saturated solution of cadmium sulphate (Fig. 284). It is so easily and exactly reproducible and has an E.M.F. of such extraordinary constancy that it has been taken by international agreement as the standard in terms of which all E.M.F.'s and P.D.'s are rated.

Thus the *E.M.F. of a Weston normal cell at* 20° *C. is taken as* 1.0183 *volts. The legal definition of the volt is then "an electrical pressure equal to* $\frac{1}{1.0183}$ *of that produced by a Weston normal cell."*

335. The Leclanché cell. The Leclanché cell (Fig. 285) consists of a zinc rod in a solution of ammonium chloride (150 grams to a liter of water) and a carbon plate placed inside of a porous cup which is packed full of manganese dioxide and powdered graphite or carbon. As in the simple cell, the zinc dissolves in the liquid, and hydrogen is liberated at the carbon, or positive, plate. Here it is slowly attacked by the manganese dioxide. This chemical action is, however, not quick enough to prevent rapid polarization when large currents are taken from the cell. The cell slowly recovers when allowed to stand for a while

Fig. 285. The Leclanché cell

on open circuit. The E.M.F. of a Leclanché cell is about 1.5 volts, and its initial internal resistance is somewhat less than an ohm. It therefore furnishes a momentary current of from one to three amperes.

The immense advantage of this type of cell lies in the fact that the zinc is not at all eaten by the ammonium chloride when the circuit is open, and that therefore, unlike the Daniell cell, it can be left for an indefinite time on open circuit without deterioration. Leclanché cells are used almost exclusively where momentary currents only are needed, as, for example, on doorbell circuits. The cell requires no attention for years at a time, other than the occasional addition of water to replace loss by evaporation, and the occasional addition of ammonium chloride (NH_4Cl) to keep positive NH_4 and negative Cl ions in the solution.

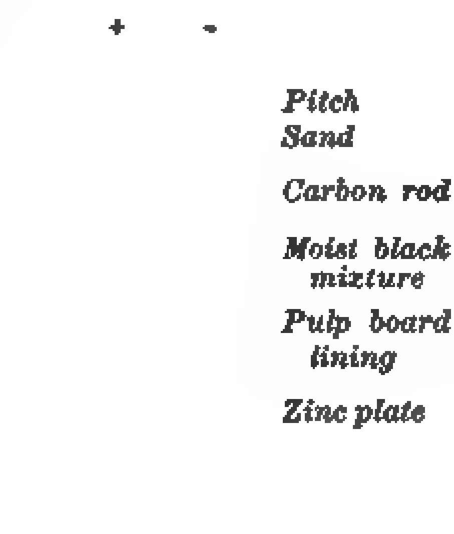


FIG. 286. The dry cell

336. The dry cell. The dry cell (Fig. 286) is a modified form of Leclanché cell. It is not really *dry*, since the mixture within is a moist paste. The ordinary dry cell contains approximately 100 grams of water. The zinc plate is in the form of a cylindrical can and holds the moist black mixture in which the carbon plate is embedded. This mixture consists of ammonium chloride, black oxide of manganese, zinc chloride, powdered petroleum coke, and a small amount of graphite. As in the Leclanché cell, it is the action of the ammonium chloride upon the zinc which produces the current. The manganese dioxide overcomes the polarization due to hydrogen. The function of the $ZnCl_2$ is to overcome the polarization due to ammonia. The graphite diminishes internal resistance, which, in a fresh cell of ordinary size, may be less

than $\frac{1}{20}$ of an ohm. Because of the low internal resistance these cells will deliver 30 or more amperes on momentary short circuit, and on account of their great convenience they are manufactured by the million annually, one firm alone making as high as 30,000 a day.

337. Combinations of cells. There are two ways in which cells may be combined: first, *in series*; and, second, *in parallel*. When they are connected in series, the zinc of one cell is joined to the copper of the second, the zinc of the second to the copper of the third, etc., the copper of the first and the zinc of the last being joined to the ends of the external resistance (see Fig. 287). The E.M.F. of such a combination is the sum of the E.M.F.'s of the single cells. The internal resistance of the combination is also the sum of the internal resistances of the single cells. Hence, if the external resistances are very small, the current furnished by the combination will be no larger than that furnished by a single cell, since the total resistance of the circuit has been increased in the same ratio as the total E.M.F. But if the external resistance is large, the current produced by the combination will be very much greater than that produced by a single cell. Just how much greater can always be determined by applying Ohm's law; for if there are n cells in series, and E is the E.M.F. of each cell, the total E.M.F. of the circuit is nE. Hence, if R_e is the external resistance and R_i the internal resistance of a single cell, then Ohm's law gives

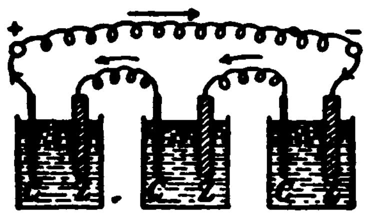


FIG. 287. Cells connected in series

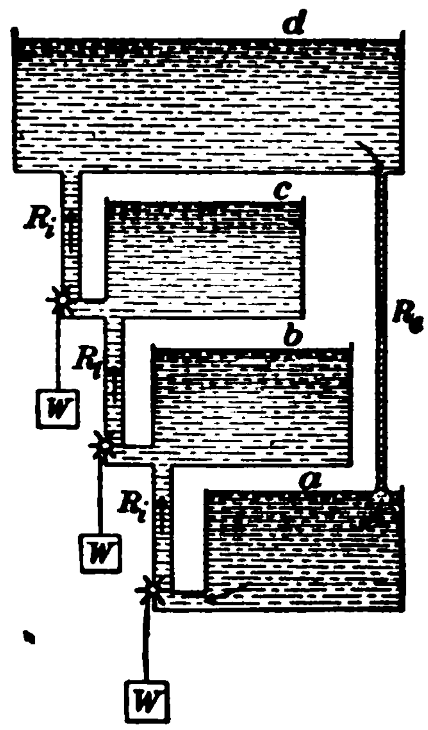


FIG. 288. Water analogy of cells in series

$$I = \frac{nE}{R_e + nR_i}.$$

If the n cells are connected in parallel, that is, if all the coppers are connected together and all the zincs, as in Fig. 289, the E.M.F. of the combination is only the E.M.F. of a single cell, while the internal resistance is $1/n$ of that of a single cell, since connecting the cells in this way is simply equivalent to multiplying the area of the plates n times. The current furnished by such a combination will be given by the formula

$$I = \frac{E}{R_e + \frac{R_i}{n}}.$$

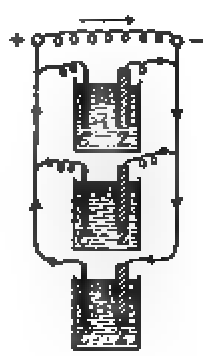


Fig. 289. Cells in parallel

Fig. 290. Water analogy of cells in parallel

If, therefore, R_e is negligibly small, as in the case of a heavy copper wire, the current flowing through it will be n times as great as that which could be made to flow through it by a single cell. Figs. 288 and 290 show by means of the water analogy why the E.M.F. of cells in series is the sum of the several E.M.F.'s, and why the E.M.F. of cells in parallel is no greater than that of a single cell. These considerations show that the rules which should govern the combination of cells are as follows: *Connect in series when R_e is large in comparison with R_i; connect in parallel when R_i is large in comparison with R_e.*

QUESTIONS AND PROBLEMS

1. A certain dry cell having an E. M. F. of 1.5 volts delivered a current of 30 amperes through an ammeter having a negligible resistance. Find the internal resistance of the cell.

2. Why is a Leclanché cell better than a Daniell cell for ringing doorbells?

3. Diagram three wires in series and three cells in series. If each wire has a resistance of .1 ohm, what is the resistance of the series? If each cell has a resistance of .1 ohm, what is the internal resistance of the series?

4. Diagram three wires in parallel or multiple, and three cells in multiple. If each wire has a resistance of 6 ohms, what is the joint resistance of the three? If each cell has an internal resistance of 6 ohms, what is the resistance of the group?

5. With the aid of Figs. 288 and 290 discuss the water analogies of the rules at the end of § 337.

6. If the internal resistance of a Daniell cell of the gravity type is 4 ohms, and its E.M.F. 1.08 volts, how much current will 40 cells in series send through a telegraph line having a resistance of 500 ohms? What current will 40 cells joined in parallel send through the same circuit? What current will one such cell send through the same circuit?

7. What current will the 40 cells in parallel send through an ammeter which has a resistance of .1 ohm? What current would the 40 cells in series send through the same ammeter? What current would a single cell send through the same ammeter?

8. Under what conditions will a small cell give practically the same current as a large one of the same type?

9. How many cells, each of E.M.F. 1.5 volts and internal resistance .2 ohm, will be needed to send a current of at least 1 ampere through an external resistance of 40 ohms?

10. Why is it desirable that a galvanometer which is to be used for measuring currents have as low a resistance as possible?

11. Ordinary No. 9 telegraph wire has a resistance of 20 ohms to the mile. What current will 100 Daniell cells in series, each of E.M.F. of 1 volt, send through 100 miles of such wire, if the two relays have a resistance of 150 ohms each and the cells an internal resistance of 4 ohms each?

12. If the relays of the preceding problem had each 10,000 turns of wire in their coils, how many ampere turns were effective in magnetizing their electromagnets?

13. If, on the above telegraph line, sounders having a resistance of 3 ohms each and 500 turns were to be put in the place of the relays, how many ampere turns would be effective in magnetizing their cores? Why, then, does the electromagnet of the relay have a high resistance?

Secondary Cells

338. Lead storage batteries. Let two 6 by 8 inch lead plates be screwed to a half-inch strip of some insulating material, as in Fig. 291, and immersed in a solution consisting of one part of sulphuric acid to ten parts of water. Let a current from two storage or three dry cells in series, *C*, be sent through this arrangement, an ammeter *A* or any

low-resistance galvanometer being inserted in the circuit. As the current flows, hydrogen bubbles will be seen to rise from the cathode (the plate at which the current leaves the solution), while the positive plate, or anode, will begin to turn dark brown. At the same time the reading of the ammeter will be found to decrease rapidly. The brown coating is a compound of lead and oxygen, called lead peroxide (PbO_2), which is formed by the action upon the plate of the oxygen which is liberated, precisely as in the experiment on the electrolysis of water (§ 302). Now let the batteries be removed from the circuit by opening the key K_1, and let an electric bell B be inserted in their place by closing the key K_2. The bell will ring and the ammeter A will indicate a current flowing in a direction opposite to that of the original current. This current will decrease rapidly as the energy which was stored in the cell by the original current is expended in ringing the bell.

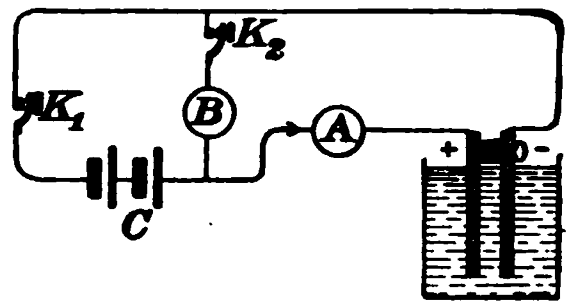


FIG. 291. The principle of the storage battery

This experiment illustrates the principle of the *storage battery*. Properly speaking, there has been no storage of *electricity*, but only a storage of *chemical energy*.

Two similar lead plates have been changed by the action of the current into two dissimilar plates, one of lead and one of lead peroxide; in other words, an ordinary galvanic cell has been formed, for any two dissimilar metals in an electrolyte constitute a primary galvanic cell. In this case the lead peroxide plate corresponds to the copper of an ordinary cell, and the lead plate to the zinc. This cell tends to create a current opposite in direction to that of the charging current; that is, its E.M.F. pushes back against the E.M.F. of the charging cells. It was for this reason that the ammeter reading fell. When the charging current is removed, this cell acts exactly like a *primary* galvanic cell and furnishes a current until the thin coating of peroxide is used up. The only important difference between a commercial storage cell (Fig. 292) and the one which we have here used is that the former is provided in

the making with a much thicker coat of the "active material" (lead peroxide on the positive plate and a porous, spongy lead on the negative) than can be formed by a single charging such as we used. This material is pressed into interstices in the plates, as shown in Fig. 292. The E.M.F. of the lead storage cell is about 2 volts. Since the plates are always very close together and may be given any desired size, the internal resistance is usually small, so that the currents furnished may be very large.

The usual efficiency of the lead storage cell is about 75%; that is, only about $\frac{3}{4}$ as much electrical energy can be obtained from it as is put into it.

Fig. 292. Lead-plate storage cell

339. Nickel-iron storage batteries. Thomas A. Edison (see opposite p. 316) developed and perfected the nickel-iron caustic-potash storage cell. The electrolyte is a 21% solution of caustic potash in water. The negative plates contain iron powder securely retained in perforated flat rectangular capsules, while the positive plates contain oxide of nickel in perforated cylindrical containers. For equal capacities the Edison cell weighs about half as much as the lead cell, and it will stand a remarkable amount of electrical and mechanical abuse. The E.M.F. is about 1.2 volts. In efficiency it is a little below the lead cell. Caustic potash is now replaced by caustic soda.

QUESTIONS AND PROBLEMS

1. In charging a storage battery is it better to say that the current passes *into* the cell or *through* it? What is "stored"?

2. The lead peroxide plate and the nickel oxide plate are both called "the positives." What is the relation of the charging current to these plates?

HEATING EFFECTS OF THE ELECTRIC CURRENT

340. Heat developed in a wire by an electric current. Let the terminals of two or three dry cells in series be touched to a piece of No. 40 iron or German-silver wire and the length of wire between these terminals shortened to $\frac{1}{4}$ inch or less. The wire will be heated to incandescence and probably melted.

The experiment shows that in the passage of the current through the wire the energy of the electric current is transformed into heat energy. The electrical energy expended when a current flows between points of given P.D. may be spent in a variety of ways. For example, it may be spent in producing chemical separation, as in the charging of a storage cell; it may be spent in doing mechanical work, as is the case when the current flows through an electric motor; or it may be spent wholly in heating the wire, as was the case in the experiment. It will always be expended in this last way when no chemical or mechanical changes are produced by it. (See drawings opposite p. 269 for uses made of heating effects.)

341. Energy relations of the electric current. We found in Chapter IX that energy expended on a water turbine is equal to the quantity of water passing through it times the difference in level through which the water falls; or, that the *power* (rate of doing work) is the product of the *fall in level* and the *current strength.* In just the same way it is found that when a current of electricity passes through a conductor, the power, or rate of doing work, is equal to the *fall in potential* between the ends of the conductor times the *strength of the electric current.* If the P.D. is expressed in volts and the current in amperes, the power is given in watts, and we have

$$\text{volts} \times \text{amperes} = \text{watts}.$$

The *energy* of the electric current is usually measured in kilowatt hours.

A kilowatt hour is the quantity of energy furnished in one hour by a current whose rate of expenditure of energy is a kilowatt.

342. Incandescent lamps. The ordinary incandescent lamp (Fig. 293) consists of a tungsten filament heated to incandescence by an electric current.

Since the filament would burn up in a few seconds in air, it is placed in a highly exhausted bulb. When in use it slowly vaporizes, depositing a dark, mirror-like coating of metal upon the inner surface of the bulb. The lead-in wires are soldered one to the base *A* of the socket and the other to its rim *B*, these being the electrodes through which the current enters and leaves the lamp. The wires *w*, *w*, sealed into the walls of the bulb, must have the same coefficient of expansion as the glass to prevent leakage of air.

FIG. 293. The tungsten vacuum lamp

Incandescent lamps are usually grouped in parallel or multiple, on a circuit that maintains a potential of something over 100 volts between the terminals of the lamps (Fig. 318). The rate of consumption of energy is about 1.25 watts per candle power for the ordinary sizes. Tungsten filaments, being operated at a much higher temperature than is possible with the now almost obsolete carbon filament, have an efficiency nearly three times as great.

A customer usually pays for his light by the kilowatt hour (§ 341). The rate at which energy is consumed by a lamp carrying $\frac{1}{4}$ ampere at 100 volts is 25 watts. Two such lamps running for 4 hours would, therefore, consume $2 \times 4 \times 25 = 200$ watt hours $= .200$ kilowatt hour. The energy is measured and recorded on a *recording watt-hour meter* (Fig. 321).

By filling the bulb with nitrogen a very efficient form of the tungsten lamp is obtained. The long filament is wound into an exceedingly fine spiral to minimize heat radiation. As we have already learned (§ 207), the presence of gas retards evaporation; hence, because of the nitrogen the filament may be raised to a higher temperature than is permissible in a vacuum. A greatly increased candle power results from the slight increase in current. Moreover, the convection currents in the gas-filled lamp cause the mirror due to vaporization to form near the top of the globe, where it does not obscure the intensity of the light. The larger sizes of gas-filled lamps consume only .6 watt per candle power.

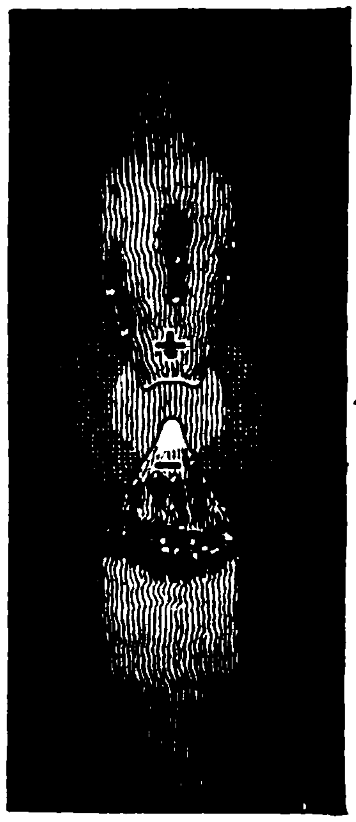


FIG. 294. The arc light

343. The arc light. When two carbon rods are placed end to end in the circuit of a powerful electric generator, the carbon about the point of contact is heated red-hot. If, then, the ends of the carbon rods are separated one-fourth inch or so, the current will still continue to flow, for a conducting layer of incandescent vapor, called an *electric arc,* is produced between the poles. The appearance of the arc is shown in Fig. 294. At the + pole a hollow, or crater, is formed in the carbon, while the – carbon becomes cone-shaped, as in the figure. The carbons are consumed at the rate of about an inch an hour, the + carbon wasting away about twice as fast as the – one. The light comes chiefly from the + crater, where the temperature is about 3800° C., the highest attainable by man. All known substances are volatilized in the electric arc.

The open arc requires a current of 10 amperes and a P.D. between its terminals of about 50 volts. Such a lamp produces about 500 * candle power, and therefore consumes energy at the rate of about 1 watt per candle power. The light of the arc lamp is due to the intense heat developed on account of resistance, not to actual combustion, or burning. Nevertheless, in the open arc the oxygen of the air unites so rapidly with

* This is the so-called "mean spherical" candle power. The candle power in the direction of maximum illumination is from 1000 to 1200.

the carbon at the hot tips that in a few hours the rods are consumed. To overcome this difficulty the *inclosed* arc (Fig. 295) is used. Shortly after the arc is "struck" the oxygen in the inner globe is used up and then the hot carbon tips are surrounded by an atmosphere of carbon dioxide and nitrogen. Under these conditions the carbons last 130 to 150 hours. The inclosed arc is much longer than the open arc, and therefore in this lamp the P.D. between the tips is greater, usually about 80 volts, while the rest of the P.D. of the line is taken up in the resistance coils of the lamp.

The recently invented *flaming arc*, produced between carbons which have a composite core consisting chiefly of carbon and fluoride of calcium, sometimes reaches an efficiency as high as .27 watt per candle power. It gives an excellent yellow light, which penetrates fog well.

Fig. 295. Mechanism of a direct-current inclosed arc lamp

344. The arc light automatic feed. Since the two carbons of the arc gradually waste away, they would soon become so far separated that the arc could no longer be maintained were it not for an automatic feeding device which keeps the distance between the carbon tips very nearly constant. Fig. 296 shows the essential features of one form of this device. When no current flows through the lamp, gravity holds the carbon tips at *e* together; but as soon as the current is thrown on, it energizes the magnet coils *m*, *m*, which draw up the U-shaped iron core, thus striking the arc at *e*. As the carbons slowly waste away, the arc becomes longer, the resistance greater, and the current less; hence the upward magnetic pull weakens and the upper carbon descends, and vice versa. From time to time the upper carbon slips down through the friction clutch *c*. It is clear, therefore, that this automatic device will maintain that particular length of arc for which

Fig. 296. Feeding device for arc lamp

equilibrium exists between the effect of gravity pulling down and magnetism pulling up. A dashpot *d*, containing a stationary piston, prevents the magnetic pull from suddenly drawing the tips at *e* too far apart.

345. The Cooper-Hewitt mercury lamp. The Cooper-Hewitt mercury lamp (Fig. 297) differs from the arc lamp in that the incandescent body is a long column of mercury vapor instead of an incandescent solid. The lamp consists of an exhausted tube three or four feet long, the positive electrode at the top consisting of a plate of iron, while the negative electrode at the bottom is a small quantity of mercury. Under a sufficient difference of potential between these terminals a long mercury-vapor arc is formed, which stretches from terminal to terminal in the tube. This arc emits a very brilliant light, but it is almost entirely wanting in red rays. The strength of its actinic rays makes it especially valuable in photography. Its commercial efficiency is about .6 watt per candle power. Cooper-Hewitt lamps having quartz tubes are used for sterilizing purposes because of the powerful ultra-violet rays which the quartz transmits.

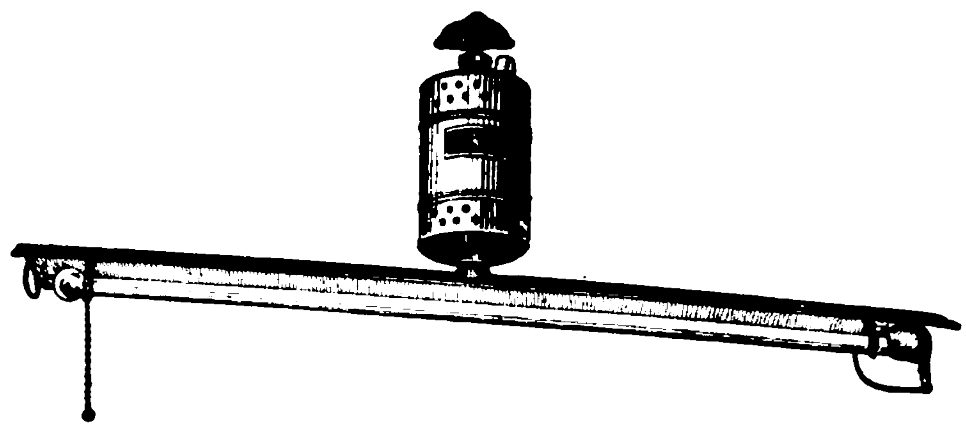


FIG. 297. The Cooper-Hewitt mercury-vapor arc lamp

QUESTIONS AND PROBLEMS

1. What is meant by a 104-volt lamp? What would happen to such a lamp if the P.D. at its terminals amounted to 500 volts? Trolley cars are usually furnished with current at about 500 volts; how would you use 100-volt lamps on such a circuit?

2. A very common electric lamp used in our homes is marked 25 watts and carries about $\frac{1}{4}$ ampere. One fresh dry cell on short circuit will deliver 30 or more amperes. Will the cell light the lamp?

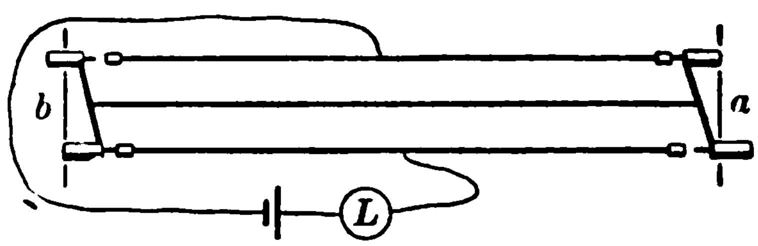


FIG. 298

3. A 50-volt carbon lamp carrying 1 ampere has about the same candle power as a 100-volt carbon lamp carrying $\frac{1}{2}$ ampere. Explain why.

4. If a storage cell has an E.M.F. of 2 volts and furnishes a current of 5 amperes, what is its rate of expenditure of energy in watts?

5. Fig. 298 shows the connections for a lamp L which can be turned on or off at two different points a or b. Explain how it works.

6. How many 100-volt lamps each carrying $\frac{1}{4}$ ampere may be maintained on a circuit where the total power may not exceed 600 watts?

7. What will it cost to use an electric laundry iron for 6 hours if it takes 3.5 amperes on a 104-volt circuit, the cost of current being \$.09 per kilowatt hour?

8. A certain electric toaster takes 5 amperes at 110 volts. It will make two pieces of toast at once in 3 minutes. At what horse-power rate does the toaster convert electrical energy into heat energy? At \$.08 per kilowatt hour what does it cost to make 12 pieces of toast?

9. How many lamps, each of resistance 20 ohms and requiring a current of .8 ampere, can be lighted by a dynamo that has an output of 4000 watts?

10. If one of the wire loops in a tungsten lamp is short-circuited, what effect will this have on the amount of current flowing through the lamp? on the brightness of the filament?

11. How many cells working as in problem 4 would be equivalent to 1 H.P.? (See § 144, p. 122.)

12. Since one calorie is equal to 42,000,000 ergs, 1 watt (10,000,000 ergs per second) develops in one second .24 calories. Therefore the number of calories, H, developed in t seconds by a current of I amperes between two points whose P.D. is V volts is expressed by the equation

$$H = I \times V \times t \times .24.$$

How many calories per minute are given out by the electric toaster of problem 8?

13. From the equation of problem 12 show that

$$H = I^2R \times t \times .24.$$

14. How many minutes are required to heat 600 g. of water from 15° C. to 100° C. by passing 5 amperes through a 20-ohm coil immersed in the water?

15. Why is it possible to get a much larger current from a storage cell than from a Daniell cell?

16. If an automobile is equipped with 6-volt lamps, how many lead storage cells must be on the car? Are these cells in series or multiple?

17. A small arc lamp requires a current of 5 amperes and a difference of potential between its terminals of 45 volts. What resistance must be connected in series with it in order to use it on a 110-volt circuit?

CHAPTER XV

INDUCED CURRENTS

The Principle of the Dynamo and Motor

346. Current induced by a magnet. Let 400 or 500 turns of No. 22 copper wire be wound into a coil *C* (Fig. 299) about two and a half inches in diameter. Let this coil be connected into circuit with a lecture-table galvanometer (Fig. 263), or even a simple detector made by suspending in a box, with No. 40 copper wire, a coil of 200 turns of No. 30 copper wire (see Fig. 299). Let the coil *C* be thrust suddenly over the *N* pole of a strong horseshoe magnet. The deflection of the pointer *p* of the galvanometer will indicate a momentary current flowing through the coil. Let the coil be held stationary over the magnet. The pointer will be found to come to rest in its natural position. Now let the coil be removed suddenly from the pole. The pointer will move in a direction opposite to that of its first deflection, showing that a reverse current is now being generated in the coil.

FIG. 299. Induction of electric currents by magnets

We learn, therefore, that *a current of electricity may be induced in a conductor by causing the latter to move through a magnetic field*, while a magnet has no such influence upon a conductor which is at rest with respect to the field. This discovery, one of the most important in the history of science, was announced by the great Faraday in 1831. From it have sprung directly most of the modern industrial developments of electricity.

Michael Faraday (1791–1867)

Famous English physicist and chemist; one of the most gifted of experimenters; son of a poor blacksmith; apprenticed at the age of thirteen to a London bookbinder, with whom he worked nine years; applied for a position in Sir Humphry Davy's laboratory at the Royal Institution in 1813; became director of this laboratory in 1825; discovered electromagnetic induction in 1831; made the first dynamo; discovered in 1833 the laws of electrolysis, now known as Faraday's laws; the farad, the practical unit of electrical capacity, is named in his honor

Induction Motor

One of the most familiar of the more recent applications of the great principle of induction discovered by Faraday is the induction motor, which has come into extensive use in both large and small sizes. The particular one here shown is known as the squirrel-cage form, in which there is no electrical connection between the stator (the stationary part) and the rotor (the revolving part). The stator is wound on a laminated core like the stator of a dynamo, while the rotor consists of copper bars laid in a slotted laminated core, their ends being joined to copper rings, one at each end. The bars are therefore in parallel. The alternating current applied to the stator windings develops a magnetic field which rotates around the iron ring of the stator. This is equivalent to a set of magnetic poles mechanically rotated around the rotor. The magnetic lines of force which therefore cut across the copper bars of the rotor generate in them an E.M.F. which causes a current to flow in the copper system of the rotor. The rotating field reacts with the field produced by the current in the conductors of the rotor so as to cause the rotor to be dragged around after the rotating field

347. Direction of induced current. Lenz's law. In order to find the *direction* of the induced current, let a very small P.D. from a galvanic cell be applied to the terminals *A* and *B* (Fig. 299), and note the direction in which the pointer moves when the current enters, say, at *A*. This will at once show in what direction the current was flowing in the coil *C* when it was being thrust over the *N* pole. By a simple application to *C* of the right-hand rule (§ 308) we can then tell which was the *N* and which the *S* face of the coil when the induced current was flowing through it. In this way it will be found that if the coil was being moved past the *N* pole of the magnet, the current induced in it was in such a direction as to make the lower face of the coil an *N* pole during the downward motion and an *S* pole during the upward motion. In the first case the repulsion of the *N* pole of the magnet and the *N* pole of the coil tended to *oppose* the motion of the coil while it was moving from *a* to *b*, and the attraction of the *N* pole of the magnet and the *S* pole of the coil tended to oppose the motion while it was moving from *b* to *c*. In the second case the repulsion of the two *N* poles tended to oppose the motion between *b* and *c*, and the attraction between the *N* pole of the magnet and the *S* pole of the coil tended to oppose the upward motion from *b* to *a*. *In every case, therefore, the motion is made against an opposing force.*

From these experiments, and others like them, we arrive at the following law: *Whenever a current is induced by the relative motion of a magnetic field and a conductor, the direction of the induced current is always such as to set up a magnetic field which opposes the motion.* This is Lenz's law. This law might have been predicted at once from the principle of the conservation of energy; for this principle tells us that since an electric current possesses energy, such a current can appear only through the expenditure of mechanical work or of some other form of energy.

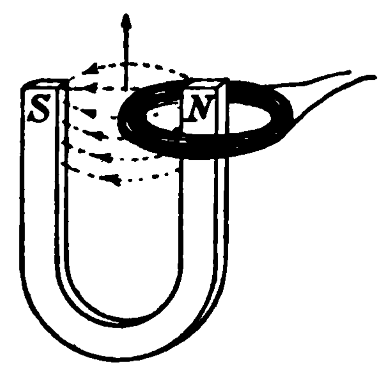


FIG. 300. Currents induced only when conductor *cuts* lines of force

348. Condition necessary for an induced E.M.F. Let the coil be held in the position shown in Fig. 300, and moved back and forth *parallel* to the magnetic field, that is, parallel to the line *NS*. No current will be induced.

By experiments of this sort it is found that an E.M.F. is induced in a coil only *when the motion takes place in such a way as to change the total number of magnetic lines of force which are inclosed by the coil.* Or, to state this rule in more general form, *an E.M.F. is induced in any element of a conductor when, and only when, that element is moving in such a way as to cut magnetic lines of force.**

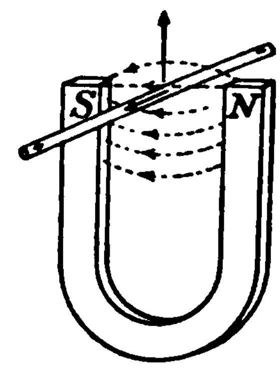


FIG. 301. E.M.F. induced when a straight conductor cuts magnetic lines

It will be noticed that the first statement of the rule is included in the second, for whenever the number of lines of force which pass through a coil changes, some lines of force must cut across the coil from the inside to the outside, or vice versa.

349. The principle of the electric motor. Let a vertical wire *ab* be rigidly attached to a horizontal wire *gh*, and let the latter be supported by a ring or other metallic support, in the manner shown in Fig. 302, so that *ab* is free to oscillate about *gh* as an axis. Let the lower end of *ab* dip into a trough of mercury. When a magnet is held in the position shown and a current from a dry cell is sent down through the wire, the wire will instantly move in the direction indicated by the arrow *f*, namely, at right angles to the direction of the lines of magnetic force. Let the direction of the current in the wire be reversed. The direction of the force acting on the wire will be found to be reversed also.

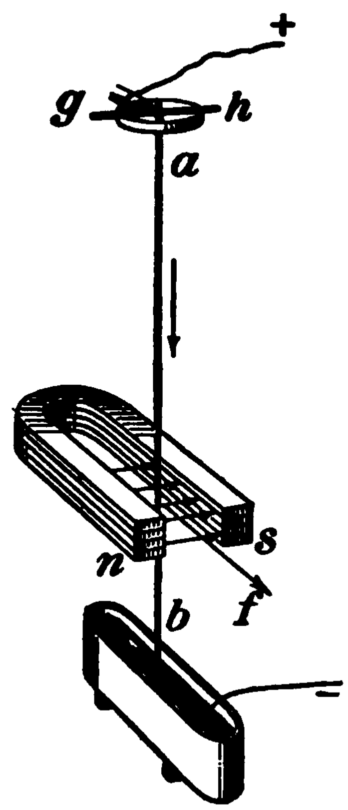


FIG. 302. The principle of the electric motor

We learn, therefore, that *a wire carrying a current in a magnetic field tends to move in*

* If a strong electromagnet is available, these experiments are more instructive if performed, not with a coil, as in Fig. 300, but with a straight rod (Fig. 301) to the ends of which are attached wires leading to a galvanometer. Whenever the rod moves parallel to the lines of magnetic force there will be no deflection, but whenever it moves across the lines the galvanometer needle will move at once.

a direction at right angles both to the direction of the field and to the direction of the current. This fact underlies the operation of all electric motors.

350. The motor and dynamo rules. A convenient rule for determining whether the wire *ab* (Fig. 302) will move forward or back in a given case may be obtained as follows: If the field of a magnet alone is represented by Fig. 303, and that due to the current * alone by Fig. 304, then the resultant field when the current-bearing wire is placed between the poles of the magnet is that shown in Fig. 305; for the strength of the

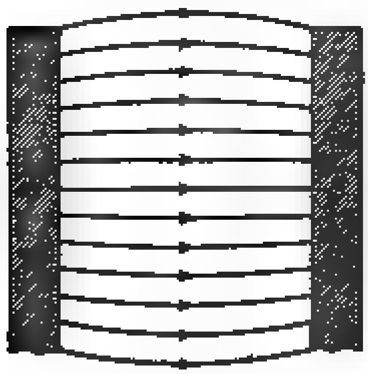


FIG. 303. Field of magnet alone

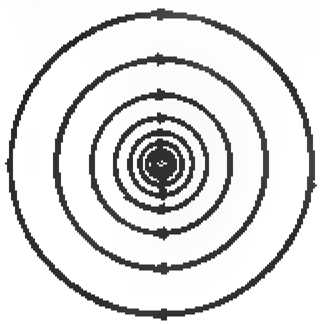


FIG. 304. Field of current alone

FIG. 305. Field of magnet and current

field above the wire is now the sum of the two separate fields, while the strength below it is their difference. Now Faraday thought of the lines of force as acting like stretched rubber bands. This would mean that the wire in Fig. 305 would be pushed *down*. Whether the lines of force are so conceived or not, *the motor rule* may be stated thus:

A current in a magnetic field tends to move away from the side on which its lines are added to those of the field.

The dynamo rule follows at once from the motor rule and Lenz's law. Thus, when a wire is moved through a magnetic field the current induced in it must be in such a direction as

* The cross in the conductor of Fig. 304, representing the tail of a retreating arrow, is to indicate that the current flows away from the reader. A dot, representing the head of an advancing arrow, indicates a current flowing toward the reader.

to oppose the motion; therefore *the induced current will be in such a direction as to increase the number of lines on the side toward which it is moving.*

351. Strength of the induced E.M.F. The strength of an induced E.M.F. is found to depend simply upon *the number of lines of force cut per second* by the conductor, or, in the case of a coil, upon the *rate of change* in the number of lines of force which pass through the coil. The strength of the current which flows is then given by Ohm's law; that is, it is equal to the induced E.M.F. divided by the resistance of the circuit. The number of lines of force which the conductor cuts per second may always be determined if we know the velocity of the conductor and the strength of the magnetic field through which it moves. For it will be remembered that, according to the convention of § 270, a field of unit strength is said to contain one line of force per square centimeter, a field of 1000 units strength 1000 lines per square centimeter, etc. In a conductor which is cutting lines at the rate of 100,000,000 per second there is an induced E.M.F. of 1 volt.* The reason why we used a coil of 500 turns instead of a single turn in the experiment of § 346 was that by thus making the conductor in which the current was to be induced cut the lines of force of the magnet 500 times instead of once, we obtained 500 times as strong an induced E.M.F., and therefore 500 times as strong a current for a given resistance in the circuit.

352. Currents induced in rotating coils. Let a 400- or 500-turn coil of No. 28 copper wire be made small enough to rotate between the poles of a horseshoe magnet, and let it be connected into the circuit of a galvanometer, precisely as in § 346. Starting with the coil in the position of Fig. 306, (1), let it be rotated suddenly clockwise (looking down from above) through 180°. A strong deflection of the galvanometer will be observed. Let it be rotated through the next 180° back to the starting point. An opposite deflection will be observed.

* This may be considered as *the scientific definition of the volt*, convenience alone having dictated the legal definition given in § 334.

The arrangement is a *dynamo* in miniature. During the first half of the revolution (see Fig. 306, (2)) the wires on the right side of the loop were cutting the lines of force in one direction, while the wires on the left side were cutting them in the opposite direction. A current was being generated down on the right side of the coil and up on the left side (see dynamo rule). It will be seen that both currents flow around the coil in the same direction. The induced current is strongest when the coil is in the position shown in Fig. 306, (2), because there the lines of force are being cut most rapidly. Just as the coil is moving into or out of the position shown in Fig. 306, (1), its edges are moving *parallel* to the lines of force, and hence no current is induced, since no lines of force are being cut. As the coil moves through the last 180° of its revolution both sides are cutting the same lines of force as before, but they are cutting them in an opposite direction; hence the current generated during this last half is opposite in direction to that of the first half.*

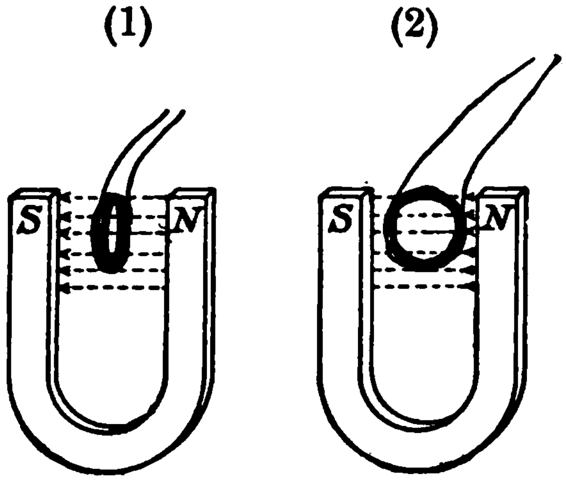


FIG. 306. Direction of currents induced in a coil rotating in a magnetic field

QUESTIONS AND PROBLEMS

1. Can the number of lines of force within a closed coil of wire be increased or decreased without the lines being cut by the wire? Explain.

2. Under what conditions may an electric current be produced by a magnet?

3. How many lines of force must be cut per second to induce 10 volts?

4. If a coil of wire is rotated about a vertical axis in the earth's field, an alternating current is set up in it. In what position is the coil when the current changes direction?

*A laboratory experiment on the principles of induction should be performed at about this point. See, for example, Experiment 36 of the authors' Manual.

5. State Lenz's law, and show how it follows from the principle of the conservation of energy.

6. A coil is thrust over the *S* pole of a magnet. Is the direction of the induced current clockwise or counterclockwise as you look down upon the pole?

7. A ship having an iron mast is sailing east. In what direction is the E.M.F. induced in the mast by the earth's magnetic field? If a wire is brought from the top of the mast to its bottom, no current will flow through the circuit. Why?

8. A current is flowing from top to bottom in a vertical wire. In what direction will the wire tend to move on account of the earth's magnetic field?

Dynamos

353. A simple alternating-current dynamo. The simplest form of commercial dynamo consists of a coil of wire so arranged as to rotate continuously between the poles of a powerful electromagnet (Fig. 307).

In order to make the magnetic field in which the conductor is moved as strong as possible, the coil is wound upon an iron core *C*. This greatly increases the total number of lines of magnetic force which pass between *N* and *S*, for instead of an air path the core offers an iron path, as shown in Fig. 308.

Fig. 307. Drum-wound armature

The rotating part, consisting of the coil with its core, is called the *armature*. One end of the coil is attached to the insulated metal ring *R*, which is attached rigidly to the shaft of the armature and therefore rotates with it, while the other end of the coil is attached to a second ring *R'*. The brushes *b* and *b'*, which constitute the terminals of the external circuit, are always in contact with these rings.

As the coil rotates, an induced alternating current passes through the circuit. This current reverses direction as often as the coil passes through the position shown in Fig. 308, that is, the position in which the conductors are moving *parallel* to the lines of force; for at this instant the conductors which were moving up begin to move down, and those which were moving down begin to move up. The current reaches its maximum value when the coils are moving through a position 90° farther on, for then the lines of force are being cut most rapidly by the conductors on both sides of the coil. These facts are graphically represented by the curve of E.M.F.'s (Fig. 309).

FIG. 308. End view of drum armature

354. The multipolar alternator. For most commercial purposes it is found desirable to have 120 or more alternations of current per second. This could not be attained easily with two-pole machines like those

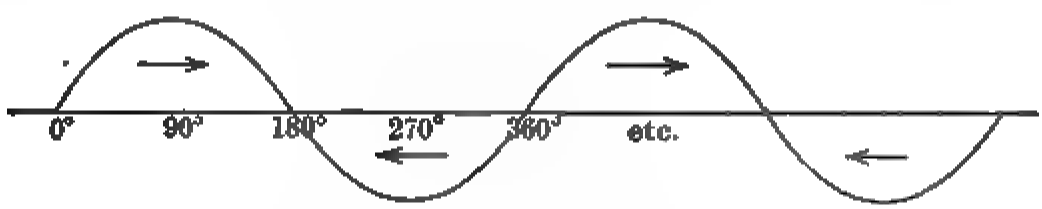


FIG. 309. Curve of alternating electromotive force

sketched in Figs. 307 and 308. Hence commercial alternators are usually built with a large number of poles alternately N and S, arranged around the circumference of a circle in the manner shown in Fig. 310. These poles are excited by a *direct* current. The dotted lines represent the direction of the lines of force through the iron. It will be seen that the coils which are passing beneath N poles have induced currents set up in them the direction of which is opposite to that of the currents which are induced in the conductors which are passing beneath the S poles. Since, however, the direction of winding of the armature coils changes between each two poles, all the inductive effects of all the poles are added in the coil and constitute at any instant one single current

flowing around the complete circuit in the manner indicated by the arrows in the diagram. This current reverses direction at the instant at which all the coils pass the midway points between the *N* and *S* poles. The number of alternations per second is equal to the number of poles multiplied by the number of revolutions per second. The field magnets *N* and *S* of such a dynamo are usually excited by a direct current from some other source. Fig. 311 represents an alternating-current dynamo with revolving field and stationary armature connected directly to a tandem compound engine. Alternators of 5000-kilowatt capacity (nearly 7000 horse power) have been built to run at the unusually high speed of 3600 revolutions per minute. Alternators of lower speed but of very much greater capacity are common (see huge rotor opposite p. 257).

Fig. 310. Diagram of alternating-current dynamo

355. The principle of the commutator. By the use of a so-called *commutator* it is possible to transform a current which is alternating in the coils of the armature to one which always flows in the same direction through the external portion of the circuit. The simplest possible form of such a commutator

Fig. 311. Alternating-current dynamo

is shown in Fig. 312. It consists of a single metallic ring which is split into two equal insulated semicircular segments a and c. One end of the rotating coil is soldered to one of these semicircles, and the other end to the other semicircle. Brushes b and b' are set in such positions that they lose contact with one semicircle and make contact with the other at the instant at which the current changes direction in the armature. The current, therefore, always passes out to the external circuit through the same brush. While a current from such a coil and commutator as that shown in the figure would always flow in the same direction through the external circuit, it would be of a pulsating rather than a steady character, for it would rise to a maximum and fall again to zero twice during each complete revolution of the armature. This effect is avoided in the commercial direct-current dynamo by building a commutator of a large number of segments instead of two, and connecting each to a portion of the armature coil in the manner shown in Fig. 313. The result of using a simple split-ring commutator is shown graphically in Fig. 314.

FIG. 312. The simple commutator

FIG. 313. Two-pole direct-current dynamo with ring armature

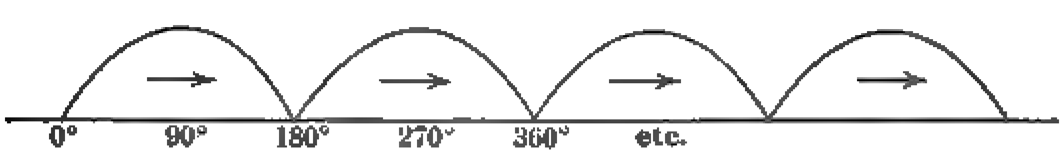


FIG. 314. Curve of commutated electromotive force

356. The drum-armature direct-current dynamo. Fig. 315 is a diagram illustrating the construction of a commercial two-pole direct-current dynamo of the drum-armature type. At a given instant currents are being induced in the same direction in all the conductors on the left half of the armature. The cross on these conductors, representing the tail of a retreating arrow, is to indicate that these currents flow away from the reader. No E.M.F.'s are induced in the conductors at the top and bottom of the armature, where the motion is parallel to the magnetic lines. On the right half of the ring, on the other hand, the induced currents are all in the opposite direction, that is, toward the reader, since the conductors are here all moving up instead of down. The dot in the middle of these conductors represents the head of an approaching arrow. It will be seen, however, in tracing out the connections $1, 1_1, 2, 2_1, 3, 3_1$, etc., of Fig. 315 (the dotted lines representing connections at the back of the drum), that the coil is so wound about the drum that the currents in both halves are always flowing toward one brush b, from which they are led to the external circuit and back at b'. This condition always exists, no matter how fast the rotation; for it will be seen that as each loop rotates into the position where the direction of its current reverses, it passes a brush and therefore at once becomes a part of the circuit on the other half of the drum where the currents are all flowing in the opposite direction. Fig. 316 shows a typical modern four-pole generator, and Fig. 317 the corresponding drum-wound armature. Fig. 326 (p. 310)

FIG. 315. The direct-current dynamo, drum winding

FIG. 316. A four-pole direct-current generator

illustrates nicely the method of winding such an armature, each coil beginning on one segment of the commutator and ending on the adjacent segment.

357. Dynamo lighting circuit. The type of circuit generally used in D.C. incandescent lighting is shown in Fig. 318. The lamps are arranged in parallel between the mains. The field magnets are excited partly by a few series turns which carry the whole current going to the lamps, and partly by a shunt coil consisting of many turns of fine wire (Fig. 318). This combination of series and shunt winding maintains the P.D. across the mains constant for a great range of loads. Such a machine is called a *compound wound* dynamo, to distinguish it from a *series wound* machine, for example, which dispenses with the shunt coil.

FIG. 317. A modern drum armature

In all self-exciting machines there is enough residual magnetism left in the iron cores after stopping to start feeble induced currents when started up again. These currents immediately increase the strength of the magnetic field, and so the machine quickly builds up its current until the limit of magnetization is reached.

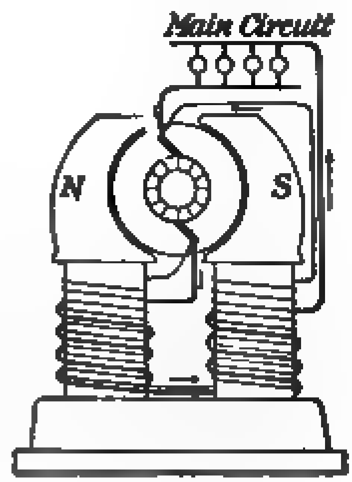


FIG. 318. The compound-wound dynamo

358. The electric motor. In construction the electric motor differs in no essential respect from the dynamo. To analyze the operation as a motor of such a machine as that shown in Fig. 313, suppose a current from an outside source is first sent around the coils of the field magnets and then into the armature at b'. Here it will divide and flow through all the conductors on the left half of the ring in one direction, and through all those on the right half in the opposite direction. Hence, in accordance with the motor rule, all the conductors on the left side are urged upward by the influence of the field, and all those on the right side are urged downward. The armature will therefore begin to rotate, and this rotation

will continue as long as the current is sent in at b' and out at b; for as fast as coils pass either b or b' the direction of the current flowing through them changes, and therefore the direction of the force acting on them changes. The left half is therefore always urged up and the right half down. The greater the strength of the current, the greater the force acting to produce rotation.

If the armature is of the drum type (Fig. 315), the conditions are not essentially different; for, as may be seen by following out the windings, the current entering at b' will flow through all the conductors on the left half in one direction and through those on the right half in the opposite direction. The commutator keeps these conditions always fulfilled. The *induction* motor is pictured and described opposite page 291.

FIG. 319. Railway motor, upper field raised

The electric motor is a device which receives electrical energy and converts it into mechanical energy. The dynamo is a device which receives mechanical energy from a steam engine, water wheel, or other source and converts it into electrical energy.

359. Street-car motors. Electric street cars are nearly all operated by direct-current series-wound motors placed under the cars and attached by gears to the axles. Fig. 319 shows a typical four-pole street-car motor. The two upper field poles are raised with the case when the motor is opened for inspection, as in the figure. The current is generally supplied by compound-wound dynamos which maintain a constant potential of about 500 volts between the trolley or third rail and the track which is used as the return circuit. The cars are always operated in parallel, as shown in Fig. 320. In a few instances street cars are operated upon

alternating, instead of upon direct-current, circuits. In such cases the motors are essentially the same as direct-current series-wound motors; for since in such a machine the current must reverse in the field magnets at the same time that it reverses in the armature, it will be seen that

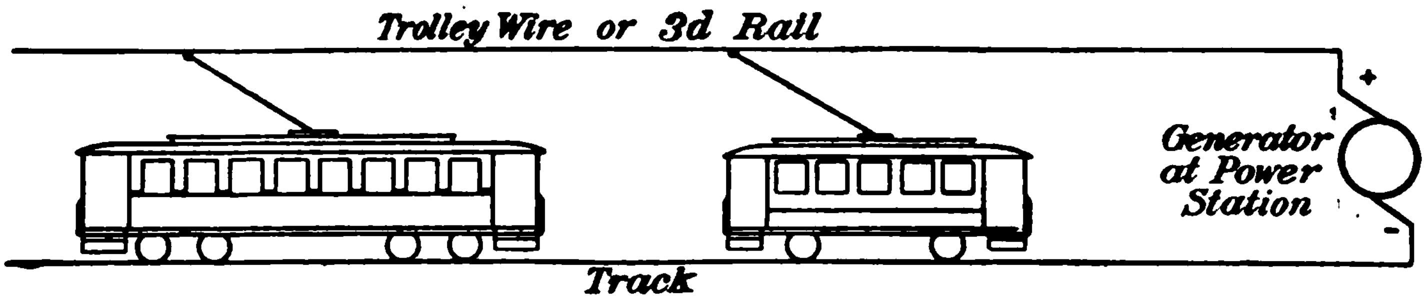


FIG. 320. Street-car circuit

the armature is always impelled to rotate in one direction, whether it is supplied with a direct or with an alternating current. Other types of A.C. motors are not well adapted to starting with full load.

360. Back E.M.F. in motors. When an armature is set into rotation by sending a current from some outside source through it, its coils move through a magnetic field as truly as if the rotation were produced by a steam engine, as is the case in running a dynamo. An induced E.M.F. is therefore set up by this rotation. In other words, while the machine is acting as a motor it is also acting as a dynamo. The direction of the induced E.M.F. due to this dynamo effect will be seen, from Lenz's law or from a consideration of the dynamo and motor rules, to be opposite to the outside P.D., which is causing current to pass through the motor. The faster the motor rotates, the faster the lines of force are cut, and hence the greater the value of this so-called *back E.M.F.* If the motor were doing no work, the speed of rotation would increase until the back E.M.F. reduced the current to a value simply sufficient to overcome friction. It will be seen, therefore, that, in general, the faster the motor goes, the less the current which passes through its armature, for this current is always due to the *difference* between the P.D. applied at the brushes — 500 volts in the case of trolley cars — and the back E.M.F. When the

motor is starting, the back E.M.F. is zero; and hence, if the full 500 volts were applied to the brushes, the current sent through would be so large as to ruin the armature through overheating. To prevent this motors are furnished with a *starting box*, consisting of resistance coils which are thrown into series with the motor on starting, and thrown out again gradually as the speed increases and the back E.M.F. rises.* Trolley cars are usually run by two motors which, on starting, work in series, so that each supplies a part of the starting resistance for the other. After speed is acquired, they work in parallel.

361. The recording watt-hour meter. The recording watt-hour meter (Fig. 321) is the instrument which fixes our electric-light bills. It is essentially an electric motor containing no iron, so that the current through the armature *A* is proportional to the P.D. between the mains, while the current through the field magnets *F* is the current flowing into the house. Therefore the force acting between *A* and *F*, or the turning power on *A* (torque), is proportional to the product of volts by amperes; that is, it is proportional to the watts consumed. The rate of rotation is made slow by the magnetic drag due to the reaction between the magnets *M* and the current induced in the rotating aluminium disk *D* which rotates between the poles of the magnets. The recording dials have therefore a speed which is proportional to the *watts* used, and their total rotation is proportional to the total energy, or *watt hours*, consumed.

FIG. 321. Interior of watt-hour meter

* This discussion should be followed by a laboratory experiment on the study of a small electric motor or dynamo. See, for example, Experiment No. 37 of the authors' Manual.

QUESTIONS AND PROBLEMS

1. What is the function (use) of the field magnet of a dynamo? Wood is cheaper than iron; why are not the field cores made of wood?

2. How would it affect the voltage of a dynamo to increase the speed of rotation of its armature? Why? to increase the number of turns of wire in the armature coils? Why? to increase the strength of the magnetic field? Why?

3. When a wire is cutting lines of force at the rate of 100,000,000 per second, there is induced in it an E.M.F. of one volt. A certain dynamo armature has 50 coils of 5 loops each and makes 600 revolutions per minute. Each wire cuts 2,000,000 lines of force twice in a revolution. What is the E.M.F. developed?

4. What does the commutator of a dynamo do? What is the purpose of the commutator of a motor?

5. Explain the process of "building up" in a dynamo.

6. Explain how an alternating current in the armature is transformed into a unidirectional current in the external circuit.

7. Explain why a series-wound motor can run on either a direct or an alternating circuit.

8. If a current is sent into the armature of Fig. 313 at b', and taken out at b, which way will the armature revolve?

9. Will it take more work to rotate a dynamo armature when the circuit is closed than when it is open? Why?

10. Single dynamos often operate as many as 10,000 incandescent lamps at 110 volts. If these lamps are all arranged in parallel and each requires a current of .5 ampere, what is the total current furnished by the dynamo? What is the activity of the machine in kilowatts and in horse power?

11. How many 110-volt lamps like those of Problem 10 can be lighted by a 12,000-kilowatt generator?

12. Why does it take twice as much work to keep a dynamo running when 1000 lights are on the circuit as when only 500 are turned on?

Principle of the Induction Coil and Transformer

362. Currents induced by varying the strength of a magnetic field. Let about 500 turns of No. 28 copper wire be wound around one end of an iron core, as in Fig. 322, and connected to the circuit of a galvanometer G. Let about 500 more turns be wrapped about another portion of the core and connected into the circuit of two dry cells. When the key K is closed, the deflection of the galvanometer will indicate that

a temporary current has been induced in one direction through the coil *s*; and when it is opened, an equal but opposite deflection will indicate an equal current flowing in the opposite direction.

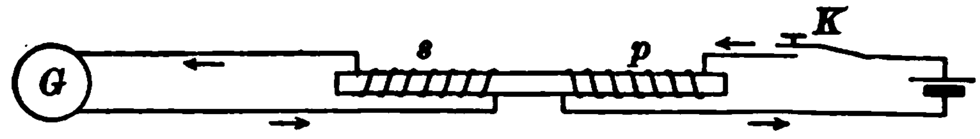


Fig. 322. Induction of current by magnetizing and demagnetizing an iron core

The experiment illustrates the principle of the induction coil and the transformer. The coil *p*, which is connected to the source of the current, is called the *primary coil*, and the coil *s*, in which the currents are induced, is called the *secondary coil*. Causing lines of force to spring into existence inside of *s* (in other words, magnetizing the space inside of *s*) has caused an induced current to flow in *s*; and demagnetizing the space inside of *s* has also induced a current in *s* in accordance with the general principle stated in § 348, that *any change in the number of magnetic lines of force which thread through a coil induces a current in the coil.* We may think of the lines as always existing as closed loops (see Fig. 258, p. 255) which collapse upon demagnetization to mere double lines at the axis of the coil. Upon magnetization one of these two lines springs out, cutting the encircling conductors and inducing a current.

363. Direction of the induced current. Lenz's law, which, it will be remembered, followed from the principle of conservation of energy, enables us to predict at once the direction of the induced currents in the above experiments; and an observation of the deflections of the galvanometer enables us to verify the correctness of the predictions. Consider first the case in which the primary circuit is *made* and the core thus magnetized. According to Lenz's law the current induced in the secondary circuit must be in such a direction as to *oppose the change* which is being produced by the primary current, that is, in such a direction as to tend to magnetize the core oppositely to the direction in which it is being magnetized by the primary. This

means, of course, that the induced current in the secondary must encircle the core in a direction opposite to the direction in which the primary current encircles it. We learn, therefore, that *on making the current in the primary the current induced in the secondary is opposite in direction to that in the primary.*

When the current in the primary is *broken*, the magnetic field created by the primary tends to die out. Hence, by Lenz's law, the current induced in the secondary must be in such a direction as to tend to oppose this process of demagnetization, that is, in such a direction as to magnetize the core in the same direction in which it is magnetized by the decaying current in the primary. Therefore, *at break the current induced in the secondary is in the same direction as that in the primary.*

364. E.M.F. of the secondary. If half of the 500 turns of the secondary *s* (Fig. 322) are unwrapped, the deflection will be found to be just half as great as before. Since the resistance of the circuit has not been changed, we learn from this that *the E.M.F. of the secondary is proportional to the number of turns of wire upon it*,— a result which followed also from § 351. If, then, we wish to develop a very high E.M.F. in the secondary, we have only to make it of a very large number of turns of fine wire.

365. Self-induction. If, in the experiment illustrated in Fig. 322, the coil *s* had been made a part of the same circuit as *p*, the E.M.F.'s induced in it by the changes in the magnetism of the core would of course have been just the same as above. In other words, when a current starts in a coil, the magnetic field which it itself produces tends to induce a current opposite in direction to that of the starting current, that is, tends to oppose the starting of the current; and when a current in a coil stops, the collapse of its own magnetic field tends to induce a current in the same direction as that of the stopping current, that is, tends to oppose the stopping of the current. This means merely that *a current in a coil acts as though it had*

inertia, and opposes any attempt to start or stop it. This inertia-like effect of a coil upon itself is called *self-induction.*

Let a few dry cells be inserted into a circuit containing a coil of a large number of turns of wire, the circuit being closed at some point by touching two bare copper wires together. Holding the bare wire in the fingers, break the circuit between the hands and observe the shock due to the current which the E.M.F. of self-induction sends through your body. Without the coil in circuit you will obtain no such shock, though the current stopped when you break the circuit will be many times larger.

366. The induction coil. The induction coil, as usually made (Fig. 323), consists of a soft iron core C composed of a bundle of soft iron wires; a primary coil p wrapped around this core and consisting of, say, 200 turns of coarse copper wire

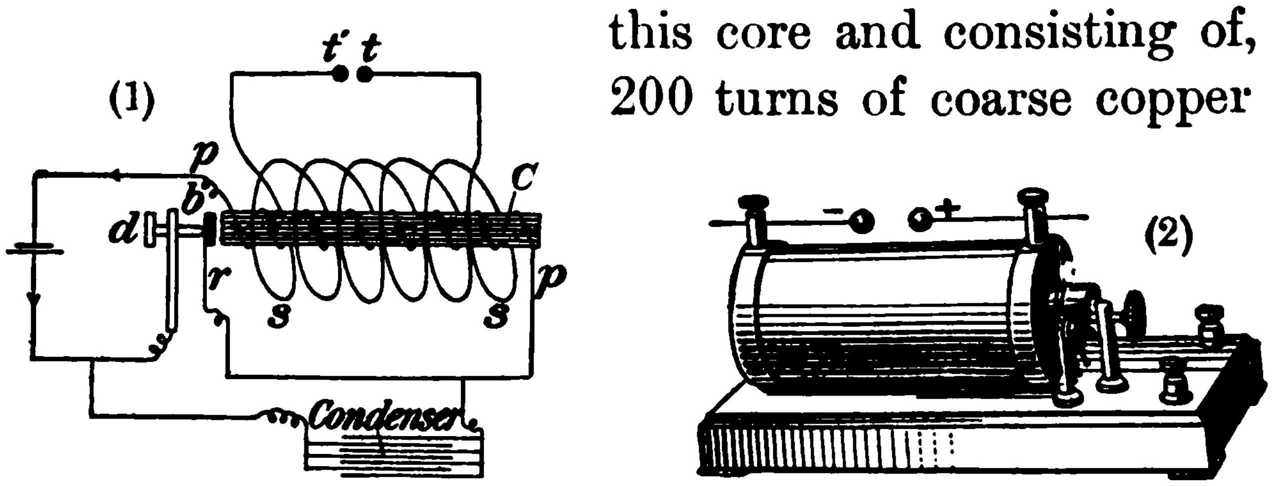


FIG. 323. Induction coil

(for example, No. 16), which is connected into the circuit of a battery through the contact point at the end of the screw d; a secondary coil s surrounding the primary in the manner indicated in the diagram and consisting generally of between 30,000 and 1,000,000 turns of No. 36 copper wire, the terminals of which are the points t and t'; and a hammer b, or other automatic arrangement for making and breaking the circuit of the primary. (See ignition system opposite p. 199.)

Let the hammer b be held away from the opposite contact point by means of the finger, then touched to this point, then pulled quickly away. *A spark will be found to pass between t and t′ at break only — never at make.* This is because, on account of the opposing influence at *make* of self-induction in the primary, the magnetic field about the primary rises

very gradually to its full strength, and hence its lines pass into the secondary coil comparatively slowly. At *break*, however, by separating the contact points very quickly we can make the current in the primary fall to zero in an exceedingly short time, perhaps not more than .00001 second; that is, we can make all of its lines pass out of the coil in this time. Hence the *rate* at which lines thread through or cut the secondary is perhaps 10,000 times as great at break as at make, and therefore the E.M.F. is also something like 10,000 times as great. In the normal use of the coil the circuit of the primary is automatically made and broken at *b* by means of the magnet and the spring *r*, precisely as in the case of the electric bell. Let the student analyze this part of the coil for himself. The condenser shown in the diagram, with its two sets of plates connected to the conductors on either side of the spark gap between *r* and *d*, is not an essential part of a coil, but when it is introduced it is found that the length of the spark which can be sent across between *t* and *t′* is considerably increased. The reason is as follows: When the circuit is broken at *b*, the inertia (that is, the self-induction) of the primary current tends to make a spark jump across from *d* to *b*; and if this happens, the current continues to flow through this spark (or arc) until the terminals have become separated through a considerable distance. This makes the current die down gradually instead of suddenly, as it ought to do to produce a high E.M.F; but when a condenser is inserted, as soon as *b* begins to leave *d* the current begins to flow into the condenser, and this gives the hammer time to get so far away from *d* that an arc cannot be formed. This means a sudden break and a high E.M.F. Since a spark passes between *t* and *t′* only at break, it must always pass in the same direction. Coils which give 24-inch sparks (perhaps 500,000 volts) are not uncommon. Such coils usually have hundreds of miles of wire upon their secondaries.

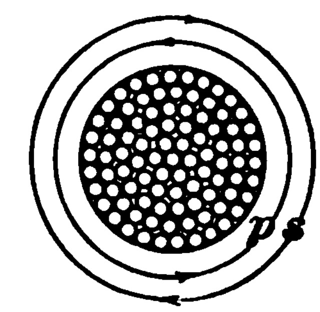


FIG. 324. Core of insulated iron wire

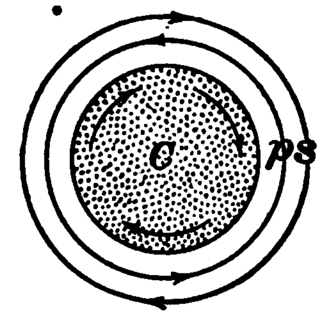


FIG. 325. Diagram showing eddy currents in solid core

367. Laminated cores; Foucault currents. The core of an induction coil should always be made of a bundle of soft-iron wires insulated from one another by means of shellac or varnish (see Fig. 324); for whenever a current is started or stopped in the primary *p* of a coil furnished with a *solid* iron core (see Fig. 325), the change in the magnetic field of the primary induces a current in the

conducting core C, for the same reason that it induces one in the secondary s. This current flows around the body of the core in the same direction as the induced current in the secondary, that is, in the direction of the arrows. The only effect of these so-called *eddy* or *Foucault* currents is to heat the core. This is obviously a waste of energy. If we can prevent the appearance of these currents, all of the energy which they would waste in heating the core may be made to appear in the current of the secondary. The core is therefore built of varnished iron wires, which run parallel to the axis of the coil, that is, perpendicular to the direction in which the currents would be induced. The induced E.M.F. therefore finds no closed circuits in which to set up a current (Fig. 324). It is for the same reason that the iron cores of dynamo and motor armatures, instead of being solid, consist of iron disks placed side by side, as shown in Fig. 326, and insulated from one another by films of oxide. A core of this kind is called a *laminated* core. It will be seen that in all such cores the spaces or slots between the laminæ must run at right angles to the direction of the induced E.M.F., that is, perpendicular to the conductors upon the core.

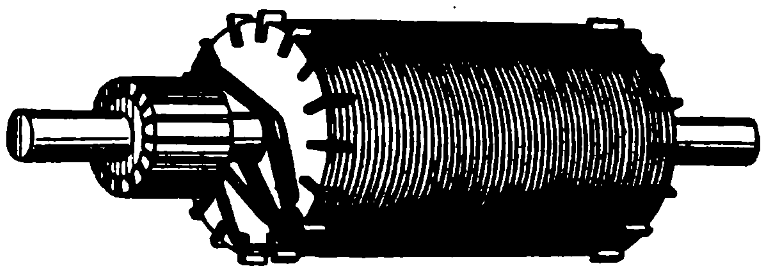


Fig. 326. Laminated drum-armature core with commutator, showing one coil wound on the core

368. The transformer. The commercial transformer is a modified form of the induction coil. The chief difference is that the core R (Fig. 327), instead of being straight, is bent into the form of a ring or is given some other shape such that the magnetic lines of force have a continuous iron path instead of being obliged to push out into the air, as in the induction coil. Furthermore, it is always an alternating instead of an intermittent current which is sent through the primary A. Sending such a current through A is equivalent to first magnetizing the core in one direction, then demagnetizing it, then magnetizing it in the opposite direction, etc. The result of

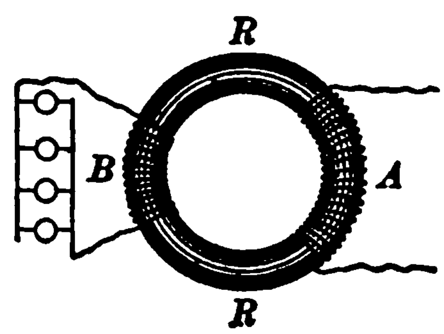


Fig. 327. Diagram of transformer

these changes in the magnetism of the core is of course an induced alternating current in the secondary *B*.

369. The use of the transformer. The use of the transformer is to convert an alternating current from one voltage to another which, for some reason, is found to be more convenient. For example, in electric lighting where an alternating current is used, the E.M.F. generated by the dynamo is usually either 1100 or 2200 volts, a voltage too high to be introduced safely into private houses. Hence transformers are connected across the main conductors in the manner shown in Fig. 328. The current which passes into the houses to supply the lamps does not come directly from the dynamo. It is an induced current generated in the transformer.

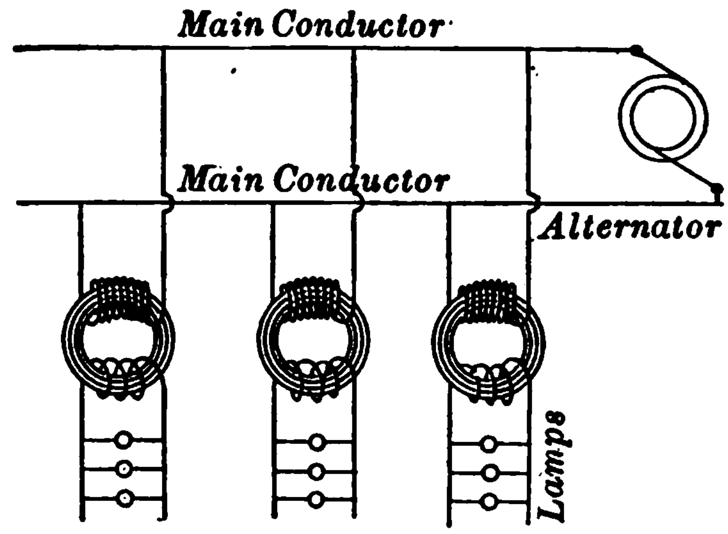


FIG. 328. Alternating-current lighting circuit with transformers

Through the use of small transformers the voltage of the current of the house lighting circuit is further reduced and made available for the ringing of doorbells.

370. Pressure in primary and secondary. If there are a few turns in the primary and a large number in the secondary, the transformer is called a *step-up* transformer, because the P.D. produced at the terminals of the secondary is greater than that applied at the terminals of the primary. In electric lighting, transformers are mostly of the *step-down* type; that is, a high P.D. (say, 2200 volts) is applied at the terminal of the primary, and a lower P.D. (say, 110 volts) is obtained at the terminals of the secondary. In such a transformer the primary will have twenty times as many turns as the secondary. In general, *the ratio between the voltages at the terminals of the primary and secondary is the ratio of the number of turns of wire upon the two.*

371. Efficiency of the transformer. In a perfect transformer the efficiency would be unity. This means that the electrical power, or watts, put into the primary (that is, the volts applied to its terminals times the amperes flowing through it) would be exactly equal to the power, or watts, taken out in the secondary (that is, the volts generated in it times the strength of the induced current); and, in fact, in actual transformers the latter product is often more than 97% of the former (that is, there is less than 3% loss of energy in the transformation). This lost energy appears as heat in the transformer. This transfer, which goes on in a big transformer, of huge quantities of power from one circuit to another entirely independent circuit, without noise or motion of any sort and almost without loss, is one of the most wonderful phenomena of modern industrial life.

372. Commercial transformers. Fig. 329 illustrates a common type of transformer used in electric lighting. The core is built up of sheet-iron laminæ about $\frac{1}{2}$ millimeter thick. Fig. 330 shows a section of the same

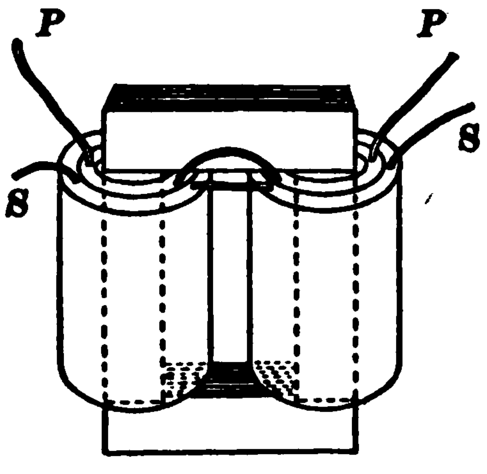


FIG. 329. The core type of transformer

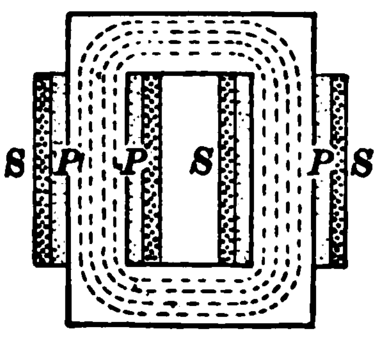


FIG. 330. Cross section of transformer, showing shape of magnetic field

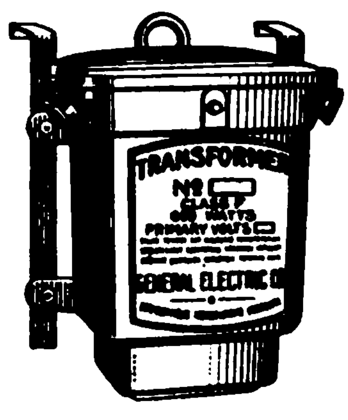


FIG. 331. Transformer case

transformer. The closed magnetic circuit of the core is indicated by the dotted lines. The primaries and the secondaries are indicated by the letters *P* and *S*. Fig. 331 is the case in which the transformer is placed. Such cases may be seen attached to poles outside of houses wherever alternating currents are used for electric lighting (Fig. 332).

373. Electrical transmission of power. Since the rate of production of electrical energy by a dynamo is the product of the E.M.F. generated by the current furnished, it is evident that in order to transmit from

one point to another a given number of watts, say, 10,000, it is possible to have either an E.M.F. of 100 volts and a current of 100 amperes or an E.M.F. of 1000 volts and a current of 10 amperes. In the two cases, however, the loss of energy in the wire which carries the current from the place where it is generated to the place where it is used will be widely different. For,

$$\text{watts} = \text{amperes} \times \text{volts};$$

but, from Ohm's law,

$$\text{volts} = \text{amperes} \times \text{ohms}.$$

Therefore

$$\text{watts} = \text{amperes}^2 \times \text{ohms} = I^2R.$$

If, then, R represents the resistance of this transmitting wire, the so-called "line resistance," and I the current flowing through it, the heat developed in it will be proportional to I^2R. Hence the energy wasted in heating the line will be but $\frac{1}{100}$ as much in the case of the 1000 volt, 10-ampere current as in the case of the 100 volt, 100-ampere current. Hence for long-distance transmission, where line losses are considerable, it is important to use the highest possible voltages.

FIG. 332. Transformer on electric-light pole

On account of the difficulty of insulating the commutator segments from one another, voltages higher than 1200 or 1500 cannot be obtained with direct-current dynamos of the kind that have been described. With alternators, however, the difficulties of insulation are very much less on account of the absence of a commutator. The large 10,000-horse-power alternating-current dynamos on the Canadian side of Niagara Falls generate directly 12,000 volts. This is the highest voltage thus far produced by generators. In all cases where these high pressures are employed they are transformed down at the receiving end of the line to a safe and convenient voltage (from 50 to 500 volts) by means of *step-down* transformers.

It will be seen from the above facts that alternating currents are best suited for long-distance transmission. The Big Creek plant in California transmits power 241 miles at a pressure of 150,000 volts. (See opposite p. 241.) The Southern Sierras Power Company of

California sends current 830 miles across the desert. Transmission at 220,000 volts is now under consideration for a line to extend the length of California, over 1100 miles. In all such cases *step-up* transformers, situated at the power house, transfer the electrical energy developed by

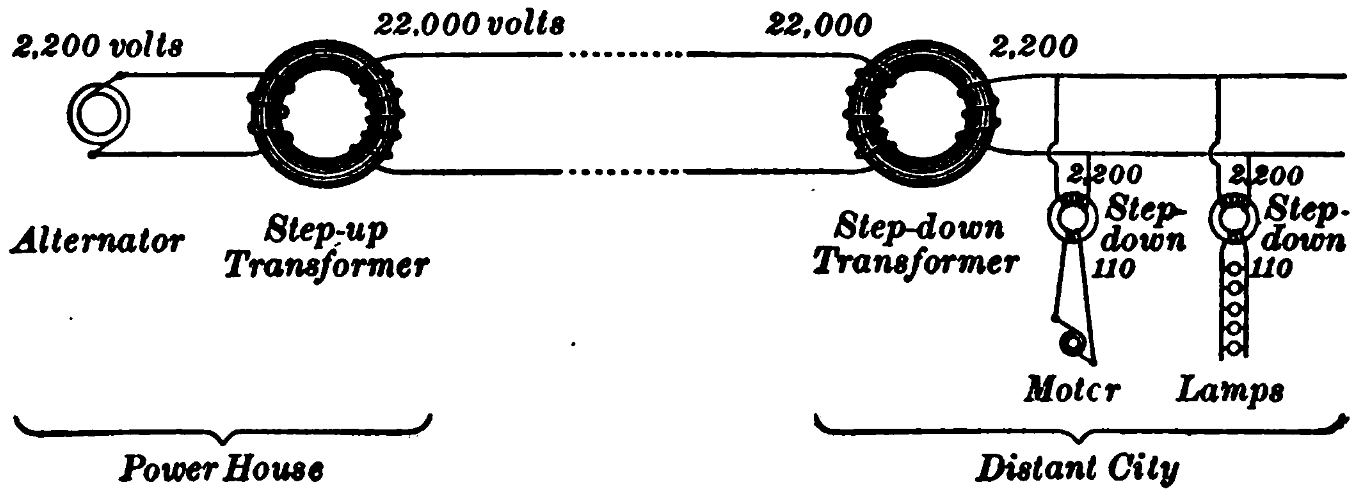


FIG. 333. High-voltage long-distance transmission line

the generator to the line, and *step-down* transformers, situated at the receiving end, transfer it to the motors or lamps which are to be supplied (Fig. 333). The generators used on the American side of Niagara Falls produce a pressure of 2300 volts. For transmission to Buffalo, 20 miles away, this is transformed up to 22,000 volts. At Buffalo it is transformed down to the voltages suitable for operating the street cars, lights, and factories of the city. On the Canadian side the generators produce currents at 12,000 volts, as stated, and these are transformed up, for long-distance transmission, to 22,000, 40,000, and 60,000 volts (see Fig. 166, p. 150).

374. The tungar rectifier. Negative electrons are found to escape from a filament that is heated to incandescence, and if this filament is then made more than, say, 25 volts negative with respect to a near-by anode any gas that surrounds the filament is found to be ionized (split into positively and negatively charged parts) by the violence of the blows which the electrons strike against its molecules. It is thus rendered conducting. These facts are utilized in the tungar rectifier of the alternating current. The bulb (Fig. 334) is filled with argon to a pressure of 3 to 8 cm. The anode is a small cone of graphite or tungsten,

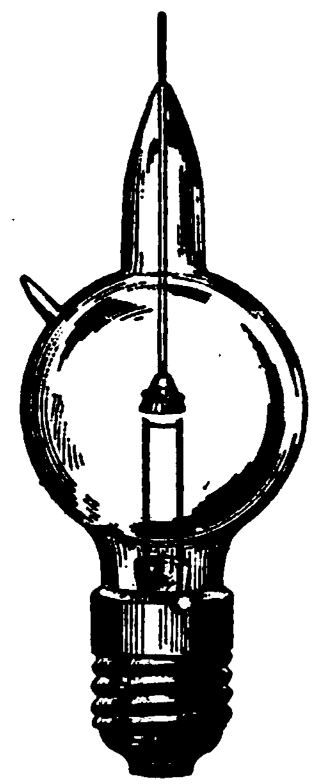


FIG. 334. Tungar bulb

and the cathode is a coiled tungsten filament. When the rectifier is in operation, the cone and the filament are alternately + and −, one being + while the other is −. When the cone is + and the filament −, the negative electrons from the filament are forced across the space from the filament to the cone, and the argon, which is thereby ionized, carries the current from the cone to the filament. When the cone is − and the filament +, the negative electrons cannot escape from the filament; hence the gas does not become conducting. The principle of operation can be understood from Fig. 335.

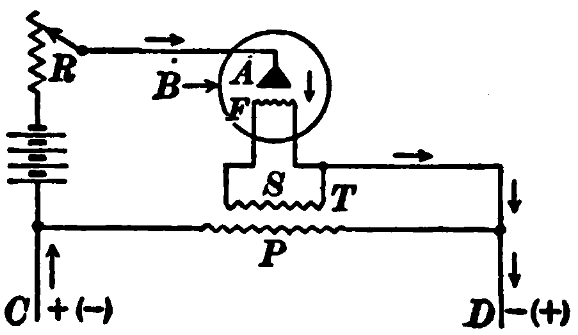


FIG. 335. Principle of operation of the tungar rectifier

The rectifier is connected to the alternating-current line at C and D. The alternating current in the primary coil P of the transformer T causes an induced current in S, which keeps the filament F incandescent. Under the action of the current, A and F are alternately + and −. When F is −, the electrons escape and ionize the gas, permitting the current to pass. When F is + the negative electrons are driven back into the filament and cannot escape to ionize the gas. Hence no current passes. In this way a unidirectional pulsating current passes through the storage batteries or other load. This rectifier is used largely for charging storage batteries for small-power purposes.

375. Principle of the carbon microphone. Let a dry cell, an ammeter, and two pieces of electric-arc carbon be arranged in series (Fig. 336). Press the carbons *very gently* and observe the reading of the ammeter. Press gradually harder, then gradually less, watching the instrument. The current increases with increase in pressure, and decreases with decrease in pressure.

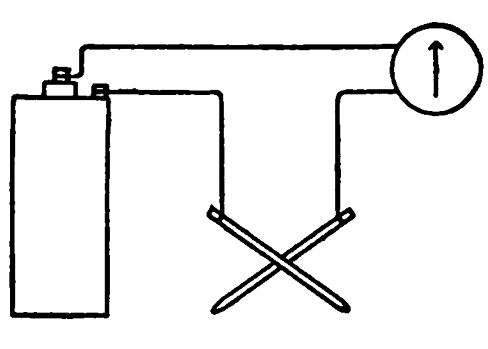


FIG. 336. The principle of the carbon transmitter

This peculiar behavior of carbon in offering a variable resistance with variation in pressure is taken advantage of in constructing the carbon transmitter of the telephone. In the modern transmitter, however, the current is made to traverse many particles of granular carbon, which, lying loosely together, furnish a very great number of loose contacts (see Fig. 339).

376. Principle of the telephone. The telephone was invented in 1875 by Alexander Graham Bell of Washington (see on opposite page) and Elisha Gray of Chicago. The simple local-battery system is shown in Fig. 337.

The current from the battery B (Fig. 337) is led first to the back of the diaphragm E, whence it passes through a little chamber C, filled with granular carbon, to the conducting back d of the transmitter, and thence through the primary p of the induction coil, and back to the battery.

When a sound is made in front of the microphone, the vibrations produced by the sounding body are transmitted by

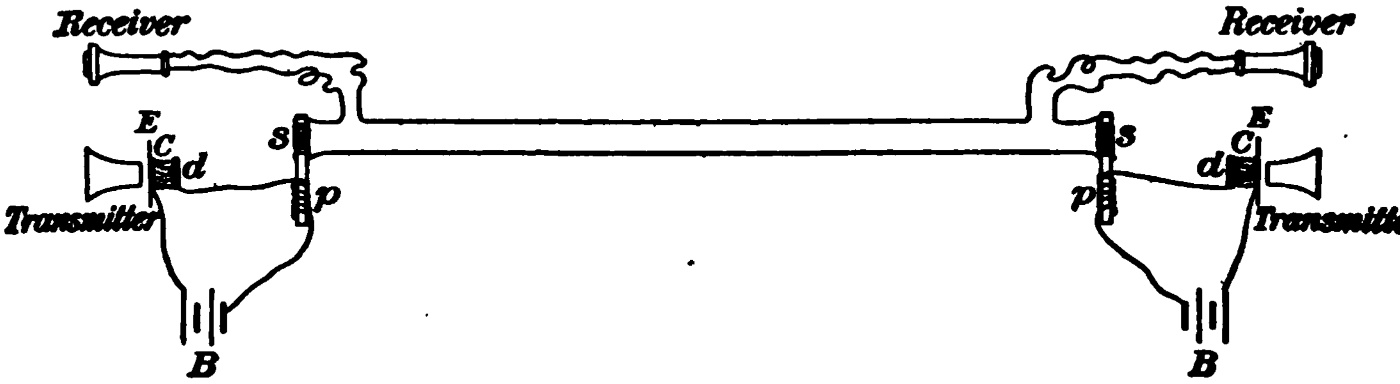


FIG. 337. The telephone circuit (local-battery system)

the air to the diaphragm, thus causing the latter to vibrate back and forth. These vibrations of the diaphragm vary the pressure upon the many contact points of the granular carbon through which the primary current flows. This produces considerable variation in the resistance of the primary circuit, so that as the diaphragm moves forward, that is, toward the carbon, a comparatively large current flows through p, and as it moves back a much smaller current. These changes in the current strength in the primary p produce changes in the magnetism of the soft-iron core of the induction coil. Currents are therefore induced in the secondary s of the induction coil, and these currents pass over the line and affect the receiver at the other end. A step-up induction coil is used to get sufficient potential to work through the high resistance of a long line.

© Clinedinst

ALEXANDER GRAHAM BELL, WASHINGTON, D.C.

Inventor of the telephone, 1875

THOMAS A. EDISON, ORANGE, NEW JERSEY

Inventor of the phonograph, the incandescent lamp, etc.

GUGLIELMO MARCONI (ITALY)

Inventor of commercial wireless telegraphy

ORVILLE WRIGHT, DAYTON, OHIO

Inventor, with his brother Wilbur, of the airplane

A GROUP OF MODERN INVENTORS

The Wright Airplane

The most significant and far-reaching of the advances of the twentieth century, namely, man's conquest of the air after centuries of failure, was made when the Wright brothers first introduced the principle upon which all successful flight by heavier-than-air machines now depends, namely, control of stability by the warping of wings, or by ailerons (hinged attachments to wings), in connection with the use of a rudder. The upper panel shows one of the original gliders (Wilbur Wright inside) with which the Wrights first mastered the art of gliding (1900–1903) and made more than a thousand gliding flights, some of them 600 feet long, following in this work the principles of gliding flight first demonstrated by Lilienthal and a little later, much more completely, by Chanute of Chicago (1895–1897). The lower panel shows "the first successful power flight in the history of the world" (Orville Wright in the machine, Wilbur running beside it as it rose from the track). Four such flights were made on the morning of December 17, 1903, the longest of which lasted 59 seconds and covered a distance of 852 feet against a 20-mile wind

A modern telephone receiver is shown in Fig. 338. It consists of a permanently magnetized U-shaped piece of steel in front of whose poles is a soft-iron diaphragm which *almost* touches the ends of the magnet. Wound in opposite directions upon the two poles are coils of fine insulated wire in series with each other and the line wire. *G* is the earpiece, *E* the diaphragm, *A* the U-shaped magnet, and *B* the coils, consisting of many turns of fine wire and having soft-iron cores. When the rapidly alternating current from the secondary coil *s* (Fig. 337) flows through the coils of the receiver, the poles of the permanent magnet are thereby alternately strengthened and weakened in synchronism with the sound waves falling upon the diaphragm of the transmitter. The variations in the magnetic pull upon the diaphragm of the receiver cause it to send out sound waves exactly like those which fell upon the diaphragm of the transmitter.

Fig. 338. The modern receiver

Telephonic conversation can be carried on over great distances as rapidly as if the parties sat on opposite sides of the same table. An electrical impulse passes over the telephone wires from New York to San Francisco in about one fifteenth of a second. The cross section of a complete long-distance transmitter is shown in Fig. 339. The current traverses granular carbon held between solid blocks of carbon.

Fig. 339. Cross section of a long-distance telephone transmitter

QUESTIONS AND PROBLEMS

1. Draw a diagram of an induction coil and explain its action.

2. Does the spark of an induction coil occur at make or at break? Why?

3. Explain why an induction coil is able to produce such an enormous E.M.F.

4. Why could not an armature core be made of coaxial cylinders of iron running the full length of the armature, instead of flat disks, as shown in Fig. 326?

5. What relation must exist between the number of turns on the primary and secondary of a transformer which feeds 110-volt lamps from a main line whose conductors are at 1100 volts P.D.?

6. Name two uses and two disadvantages of mechanical friction; of electrical résistance.

7. A transformer is so wound as to step the voltage of the lighting circuit from 2200 volts down to 110. Sketch the transformer and its connections, marking the primary and the secondary, and state the relative number of turns in each. If the house circuit uses 40 amperes, what current must flow in the primary?

8. Why does a "tungar" reetify an alternating current?

9. The same amount of power is to be transmitted over two lines from a power plant to a distant city. If the heat losses in the two lines are to be the same, what must be the ratio of the cross sections of the two lines if one current is transmitted at 100 volts and the other at 10,000 volts? (Power $= IE$; heat loss is proportional to I^2R.)

10. In telephoning from New York to San Francisco how far do you think the sound goes? What passes along the telephone wire?

CHAPTER XVI*

NATURE AND TRANSMISSION OF SOUND

Speed and Nature of Sound

377. Sources of sound. If a sounding tuning fork provided with a stylus is stroked across a smoked-glass plate, it produces a wavy line, as shown in Fig. 340; if a light suspended ball is brought into contact with it, the latter is thrown off with considerable violence. If we look about for the source of any sudden noise, we find that some object has fallen, or some collision has occurred, or some explosion has taken place, — in a word, that some violent motion of matter has been set up in some way. From these familiar facts we conclude that *sound arises from the motions of matter.*

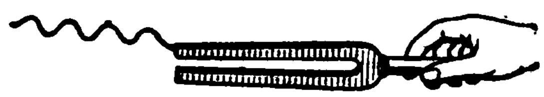


Fig. 340. Trace made by vibrating fork

378. Media of transmission. Air is ordinarily the medium through which sound comes to our ears, yet the Indians put their ears to the ground to hear a distant noise, and most boys know how loud the clapping of stones sounds under water. If the base of the sounding fork of Fig. 340 is held in a dish of water, the sound will be markedly transmitted by the water. These facts show that a gas like air is certainly no more effective in the transmission of sound than a liquid or a solid. Next let us see whether or not matter is necessary at all for the transmission of sound.

* This chapter should be accompanied by laboratory experiments on the speed of sound in air, the vibration rate of a fork, and the determination of wave lengths. See, for example, Experiments 38, 39, and 40 of the authors' Manual.

Let an electric bell be suspended inside the receiver of an air pump by means of two fine springs which pass through a rubber stopper in the manner shown in Fig. 341. Let the air be exhausted from the receiver by means of the pump. The sound of the bell will be found to become less and less pronounced. Let the air be suddenly readmitted. The volume of sound will at once increase.

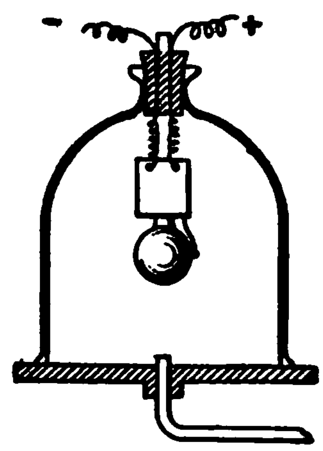


FIG. 341. Sound not transmitted through a vacuum

Since the nearer we approach a vacuum, the less distinct becomes the sound, we infer that sound cannot be transferred through a vacuum and that therefore *the transmission of sound is effected only through the agency of ordinary matter.* In this respect sound differs from heat and light, which evidently pass with perfect readiness through a vacuum, since they reach the earth from the sun and stars.

379. Speed of transmission. The first attempt to measure accurately the speed of sound was made in 1738, when a commission of the French Academy of Sciences stationed two parties about three miles apart and observed the interval between the flash of a cannon and the sound of the report. By taking observations between the two stations, first in one direction and then in the other, the effect of the wind was eliminated. A second commission repeated these experiments in 1832, using a distance of 18.6 kilometers, or a little more than 11.5 miles. The value found was 331.2 meters per second at 0° C. The accepted value is now 331.3 meters. The speed in water is about 1400 meters per second, and in iron 5100 meters.

The speed of sound in air is found to increase with an increase in temperature. The amount of this increase is about 60 centimeters per degree centigrade. Hence the speed at 20° C. is about 343.3 meters per second. The above figures are equivalent to 1087 feet per second at 0° C., or 1126 feet per second at 20° C.

380. Mechanism of transmission. When a firecracker or toy cap explodes, the powder is suddenly changed to a gas, the volume of which is enormously greater than the volume of the powder. The air is therefore suddenly pushed back in all directions from the center of the explosion. This means that the air particles which lie about this center are given violent outward velocities.* When these outwardly impelled air particles collide with other particles, they give up their outward motion to these second particles, and these in turn pass it on to others, etc. It is clear, therefore, that the motion started by the explosion must travel on from particle to particle to an indefinite distance from the center of the explosion. Furthermore, it is also clear that, although the motion travels on to great distances, the individual particles do not move far from their original positions; for it is easy to show experimentally that whenever an elastic body in motion collides with another similar body at rest, the colliding body simply transfers its motion to the body at rest and comes itself to rest.

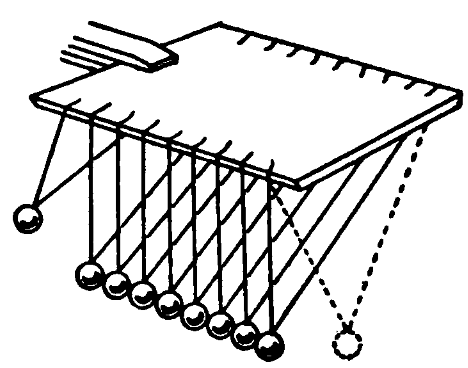


FIG. 342. Illustrating the propagation of sound from particle to particle

Let six or eight equal steel balls be hung from cords in the manner shown in Fig. 342. First let all of the balls but two adjacent ones be held to one side, and let one of these two be raised and allowed to fall against the other. The first ball will be found to lose its motion in the collision, and the second will be found to rise to practically the same height as that from which the first fell. Next let all of the balls be placed in line and the end one raised and allowed to fall as before. The motion will be transmitted from ball to ball, each giving up the whole of its motion practically as soon as it receives it, and the last ball will move on alone with the velocity which the first ball originally had.

* These outward velocities are simply superposed upon the velocities of agitation which the molecules already have on account of their temperature. For our present purpose we may ignore entirely the existence of these latter velocities and treat the particles as though they were at rest, save for the velocities imparted by the explosion.

The preceding experiment furnishes a very nice mechanical illustration of the manner in which the air particles which receive motions from an exploding firecracker or a vibrating tuning fork transmit these motions in all directions to neighboring layers of air, these in turn to the next adjoining layers, etc., until the motion has traveled to very great distances, although the individual particles themselves move only very minute distances. When a motion of this sort, transmitted by air particles, reaches the drum of the ear, it produces the sensation which we call *sound.*

381. A train of waves; wave length. In the preceding paragraphs we have confined attention to a single pulse traveling out from a center of explosion. Let us next consider the sort of disturbance which is set up in the air by a continuously vibrating body, like the prong of Fig. 343. Each time that this prong moves to the right it sends out a pulse which travels through the air at the rate of 1100 feet per second, in exactly the manner described in the preceding paragraphs. Hence, if the prong is vibrating uniformly, we shall have a continuous succession of pulses following each other through the air at exactly equal intervals. Suppose, for example, that the prong makes 110 complete vibrations per second. Then at the end of one second the first pulse sent out will have reached a distance of 1100 feet. Between this point and the prong there will be 110 pulses distributed at equal intervals; that is, each two adjacent pulses will be just 10 feet apart. If the prong made 220 vibrations per second, the distance between adjacent pulses would be 5 feet, etc. The *distance between two adjacent pulses in such a train of waves is called a wave length.*

FIG. 343. Vibrating reed sending out a train of equidistant pulses

382. Relation between velocity, wave length, and number of vibrations per second. If n represents the number of vibrations per second of a source of sound, l the wave length, and v the velocity with which the sound travels through the medium, it is evident from the example of the preceding paragraph that the following relation exists between these three quantities:

$$l = v/n, \text{ or } v = nl; \tag{1}$$

that is, *wave length is equal to velocity divided by the number of vibrations per second, or velocity is equal to the number of vibrations per second times the wave length.*

383. Condensations and rarefactions. Thus far, for the sake of simplicity, we have considered a train of waves as a series of thin, detached pulses separated by equal intervals of air at rest. In point of fact, however, the air in front of the prong B (Fig. 343) is being pushed forward not at one particular

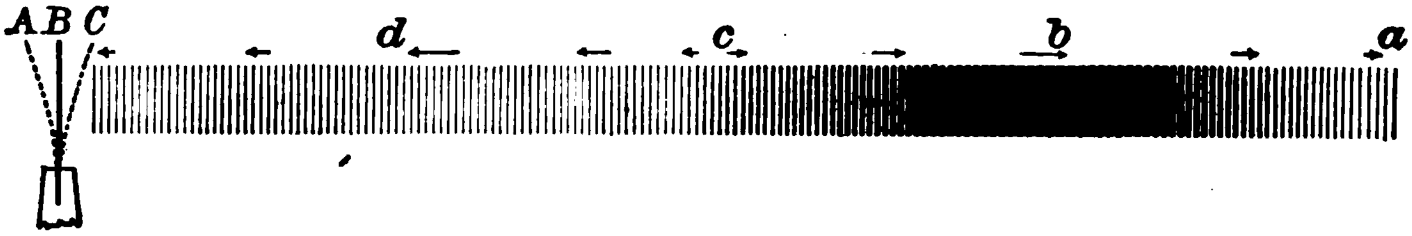


Fig. 344. Illustrating motions of air particles in one complete sound wave consisting of a condensation and a rarefaction

instant only but during all the time that the prong is moving from A to C, that is, through the time of one-half vibration of the fork; and during all this time this forward motion is being transmitted to layers of air which are farther and farther away from the prong, so that when the latter reaches C, all the air between C and some point c (Fig. 344) one-half wave length away is crowding forward and is therefore in a state of compression, or *condensation*. Again, as the prong moves back from C to A, since it tends to leave a vacuum behind it, the adjacent layer of air rushes in to fill up this space, the layer next adjoining follows, etc., so that when the prong reaches A, all the air between A and c (Fig. 344) is moving backward and

is therefore in a state of diminished density, or *rarefaction.* During this time the preceding forward motion has advanced one half wave length to the right, so that it now occupies the region between c and a (Fig. 344). Hence at the end of one complete vibration of the prong we may divide the air between it and a point one wave length away into two portions, one a region of condensation ac, and the other a region of rarefaction ca. The arrows in Fig. 344 represent the direction and relative magnitudes of the motions of the air particles in various portions of a complete wave.

FIG. 345. Illustration of sound waves

At the end of n vibrations the first disturbance will have reached a distance n wave lengths from the fork, and each wave between this point and the fork will consist of a condensation and a rarefaction, so that sound waves may be said to consist of a series of condensations and rarefactions following one another through the air in the manner shown in Fig. 345.

Wave length may now be more accurately defined as *the distance between two successive points of maximum condensation* (b and f, Fig. 345) *or of maximum rarefaction* (d and h).

384. Water-wave analogy. Condensations and rarefactions of sound waves are exactly analogous to the familiar crests and troughs of water waves. Thus, the wave length of such a series of waves as that shown in Fig. 346 is defined as the distance bf between two crests, or the distance dh, or ae, or cg, or mn, between any two points which are in the same condition, or *phase*, of disturbance. The crests (that is, the shaded portions, which are above the natural level of the water) correspond exactly

FIG. 346. Illustrating wave length of water waves

to the condensations of sound waves (that is, to the portions of air which are above the natural density). The troughs (that is, the dotted portions) correspond to the rarefactions of sound waves (that is, to the portions of air which are below the natural density). But the analogy breaks down at one point, for in water waves the motion of the particles is transverse to the direction of propagation, while in sound waves, as shown in § 383, the particles move back and forth *in* the line of propagation of the wave. *Water waves are therefore called transverse waves, while sound waves in air are called longitudinal waves.*

385. Distinction between musical sounds and noises. Let a current of air from a $\frac{1}{8}$-inch nozzle be directed against a row of forty-eight equidistant $\frac{1}{8}$-inch holes in a metal or cardboard disk, mounted as in Fig. 347 and set into rotation either by hand or by an electric motor. A very distinct musical tone will be produced. Then let the jet of air be directed against a second row of forty-eight holes, which differs from the first only in that the holes are irregularly instead of regularly spaced about the circumference of the disk. The musical character of the tone will altogether disappear.

FIG. 347. Regularity of pulses the condition for a musical tone

The experiment furnishes a very striking illustration of the difference between a musical sound and a noise. *Only those sounds possess a musical quality which come from sources capable of sending out pulses, or waves, at absolutely regular intervals.* Therefore it is only sounds possessing a musical quality which may be said to have wave lengths.

386. Pitch. While the apparatus of the preceding experiment is rotating at constant speed, let a current of air be directed first against the outside row of regularly spaced holes and then suddenly turned against the inside row, which is also regularly spaced but which contains a smaller number of holes. The note produced in the second case will

be found to have a markedly lower pitch than the other one. Again let the jet of air be directed against one particular row, and let the speed of rotation be changed from very slow to very fast. The note produced will gradually rise in pitch.

We conclude, therefore, that *the pitch of a musical note depends simply upon the number of pulses which strike the ear per second.* If the sound comes from a vibrating body, *the pitch of the note depends upon the rate of vibration of the body.*

387. The Doppler effect. When a rapidly moving express train rushes past an observer, he notices a very distinct and sudden change in the pitch of the bell as the engine passes him, the pitch being higher as the engine approaches than as it recedes. The explanation is as follows: The bell sends out pulses at exactly equal intervals of time. As the train is approaching, however, the pulses reach the ear at shorter intervals than the intervals between emissions, since the train comes toward the observer between two successive emissions. But as the train recedes, the interval between the receipt of pulses by the ear is longer than the interval between emissions, since the train is moving away from the ear during the interval between emissions. Hence the pitch of the bell is higher during the approach of the train than during its recession. This phenomenon of the change in pitch of a note proceeding from an approaching or receding body is known as *the Doppler effect.*

388. Loudness. The loudness or intensity of a sound depends upon the rate at which energy is communicated by it to the tympanum of the ear. *Loudness is therefore determined by the distance of the source and the amplitude of its vibration.*

If a given sound pulse is free to spread equally in all directions, at a distance of 100 feet from the source the same energy must be distributed over a sphere of four times as large an area as at a distance of 50 feet. Hence under these ideal conditions *the intensity of a sound varies inversely as the square of the distance from the source.* But when sound is confined within a tube so that the energy is continually communicated from one layer to another of equal area, it will travel to great distances with little loss of intensity. This explains the efficiency of speaking tubes and megaphones.

QUESTIONS AND PROBLEMS

1. A thunderclap was heard $5\frac{1}{2}$ sec. after the accompanying lightning flash was seen. How far away did the flash occur, the temperature at the time being 20° C.?

2. Why does the sound die away very gradually after a bell is struck?

3. Why does placing the hand back of the ear enable a partially deaf person to hear better?

4. Explain the principle of the ear trumpet.

5. The vibration rate of a fork is 256. Find the wave length of the note given out by it at 20° C.

6. Since the music of an orchestra reaches a distant hearer without confusion of the parts, what may be inferred as to the relative velocities of the notes of different pitch?

7. What is the relation between pitch and wave length? How is this made evident by the fact noted in question 6?

8. If we increase the amplitude of vibration of a guitar string, what effect has this upon the amplitude of the wave? upon the loudness? upon the length of the wave? upon the pitch?

Reflection, Reënforcement, and Interference

389. Echo. That a sound wave in hitting a wall suffers reflection is shown by the familiar phenomenon of echo. The roll of thunder is due to successive reflections of the original sound from clouds and other surfaces which are at different distances from the observer.

In ordinary rooms the walls are so close that the reflected waves return before the effect of the original sound on the ear has died out. Consequently the echo blends with and strengthens the original sound instead of interfering with it. This is why, in general, a speaker may be heard so much better indoors than in the open air. Since the ear cannot appreciate successive sounds as distinct if they come at intervals shorter than a tenth of a second, it will be seen from the fact that sounds travel about 113 feet in a tenth of a second that a wall which is nearer than about 50 feet cannot possibly produce a perceptible echo. In rooms which are large enough

to give rise to troublesome echoes it is customary to hang draperies of some sort, so as to break up the sound waves and prevent regular reflection.

390. Sound foci. Let a watch be hung at the focus of a large concave mirror. On account of the reflection from the surface of the mirror a fairly well-defined beam of sound will be thrown out in front of the mirror, so that if both watch and mirror are hung on a single support and the whole turned in different directions toward a number of observers, the ticking will be distinctly heard by those directly in front of the mirror, but not by those at one side. If a second mirror is held in the path of this beam, as in Fig. 348, the sound may be again brought to a focus, so that if the ear is placed in the focus of this second mirror, or, better still, if a small funnel which is connected with the ear by a rubber tube is held in this focus, the ticking of the watch may sometimes be heard hundreds of feet away. A whispering gallery is a room so arranged as to contain such sound foci. Any two opposite points a few feet from the walls of a dome, like that of St. Peter's at Rome or St. Paul's at London, are sufficiently near to such sound foci to make very low whispers on one side distinctly audible at the other, although at intermediate points no sound can be heard. There are well-known sound foci under the dome of the Capitol at Washington and in the Mormon Tabernacle at Salt Lake City.

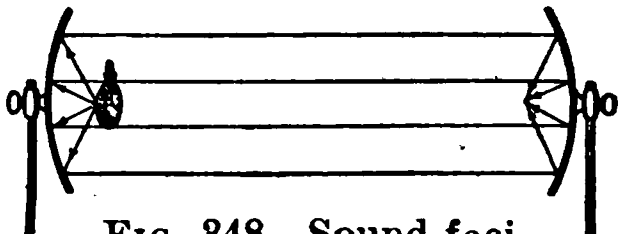


FIG. 348. Sound foci

391. Resonance. Resonance is the *reënforcement* or *intensification* of sound because of the union of *direct* and *reflected* waves.

Thus, let one prong of a vibrating tuning fork, which makes, for example, 512 vibrations per second, be held over the mouth of a tube an inch or so in diameter, arranged as in Fig. 349, so that as the vessel *A* is raised or lowered, the height of the water in the tube may be adjusted at will. It will be found that as the position of the water is slowly lowered from the top of the tube a very marked reënforcement of the sound will occur at a certain point.

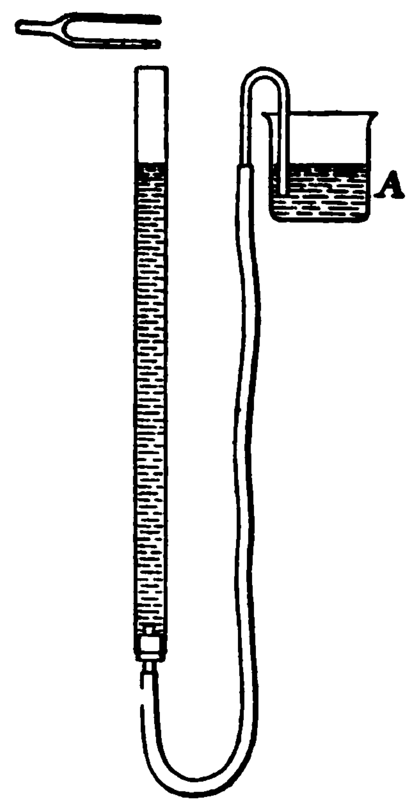


FIG. 349. Illustrating resonance

Let other forks of different pitch be tried in the same way. It will be found that the lower the pitch of the fork, the lower must be the water in the tube in order to get the best reënforcement. This means that the longer the wave length of the note which the fork produces, the longer must be the air column in order to obtain resonance.

We conclude, therefore, that *a fixed relation exists between the wave length of a note and the length of the air column which will reënforce it.*

392. Best resonant length of a closed pipe is one-fourth wave length. If we calculate the wave length of the note of the fork by dividing the speed of sound by the vibration rate of the fork, we shall find that, in every case, *the length of air column which gives the best response is approximately one-fourth wave length.* The reason for this is evident when we consider that the length must be such as to enable the reflected wave to return to the mouth just in time to unite with the direct wave which is at that instant being sent off by the prong. Thus, when the prong is first starting down from the position A (see Fig. 350), it starts the beginning of a condensation down the tube. If this motion is to return to the mouth just in time to unite with the direct wave sent off by the prong, it must get back at the instant the prong is starting up from the position C. In other words, the pulse must go down the tube and come back again while the prong is making a half vibration. This means that the path down and back must be a half wave length, and hence that the length of the tube must be a fourth of a wave length.

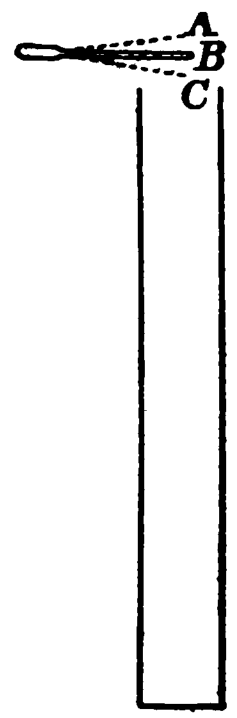


FIG. 350. Resonant length of a closed pipe is $\frac{1}{4}$ wave length

From the above analysis it will appear that there should also be resonance if the reflected wave does not return to the mouth until the fork is starting back its second time from C, that is, at the end of one and a half vibrations instead of a

half vibration. The distance from the fork to the water and back would then be one and a half wave lengths; that is, the water surface would be a half wave length farther down the tube than at first. The tube length would therefore now be three fourths of a wave length.

Let the experiment be tried. A similar response will indeed be found, as predicted, a half wave length farther down the tube. This response will be somewhat weaker than before, as the wave has lost some of its energy in traveling a long distance through the tube. It may be shown in a similar way that there will be resonance where the tube length is $\frac{5}{4}$, $\frac{7}{4}$, or indeed any odd number of quarter wave lengths.

393. Best resonant length of an open pipe is one-half wave length. Let the same tuning fork which was used in § 392 be held in front of an open pipe (8 or 10 inches long) the length of which is made adjustable by slipping back and forth over it a tightly fitting roll of writing paper (Fig. 351). It will be found that for one particular length this open pipe will respond quite as loudly as did the closed pipe, but *the responding length will be found to be just twice as great as before.* Other resonant lengths can be found when the tube is made 2, 3, etc. times as long.

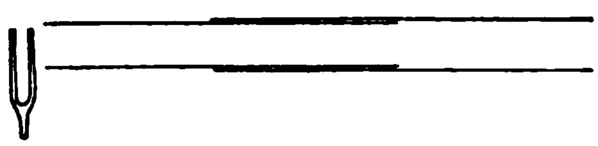


FIG. 351. Resonant length of an open pipe is $\frac{1}{2}$ wave length

We learn, then, that *the shortest resonant length of an open pipe is one-half wave length, and that there is resonance at any multiple of a half wave length.*

The fact that the shortest resonant length of the open pipe is just twice that of the closed one is the experimental proof that a condensation, upon reaching the open end of a pipe, is reflected as a rarefaction. This means that when the lower end of the tube of Fig. 350 is open, a condensation upon reaching it suddenly expands. In consequence of this expansion the new pulse which begins at this instant to travel back through the tube is one in which the particles are moving down instead of up; that is, the particles are moving in a direction opposite to that in which the wave is traveling. This is always the case in a rarefaction (see Fig. 344). In

order then to unite with the motion of the prong this downward motion of the particles must get back to the mouth when the prong is just starting down from A the second time; that is, *after one complete vibration of the prong.* This shows why the pipe length is one-half wave length.

394. Resonators. If the vibrating fork at the mouth of the tubes in the preceding experiments is replaced by a *train of waves* coming from a distant source, precisely the same analysis leads to the conclusion that the waves reflected from the bottom of the tube will reënforce the oncoming waves when the length of the tube is any odd number of quarter wave lengths in the case of a closed pipe, or any number of half wave lengths in the case of an open pipe. It is clear, therefore, that every air chamber will act as a resonator for trains of waves of a *certain* wave length. This is why a conch shell held to the ear is always heard to hum with a particular note. Feeble waves which produce no impression upon the unaided ear gain sufficient strength when reënforced by the shell to become audible. When the air chamber is of irregular form it is not usually possible to calculate to just what wave length it will respond, but it is always easy to determine experimentally what particular wave length it is capable of reënforcing. The resonators on which tuning forks are mounted are air chambers which are of just the right dimensions to respond to the note given out by the fork.

395. Forced vibrations; sounding boards. Let a tuning fork be struck and held in the hand. The sound will be entirely inaudible except to those quite near. Let the base of the sounding fork be pressed firmly against the table. The sound will be found to be enormously intensified. Let another sounding fork of different pitch be held against the same table. Its sound will also be reënforced. In this case, then, the table intensifies the sound of any fork which is placed against it, while an air column of a certain size could intensify only a single note.

The cause of the response in the two cases is wholly different. In the last case the vibrations of the fork are transmitted

through its base to the table top and force the latter to vibrate in its own period. The vibrating table top, on account of its large surface, sets a comparatively large mass of air into motion and therefore sends a wave of great intensity to the ear, while the fork alone, with its narrow prongs, was not able to impart much energy to the air. Vibrations like those of the table top are called *forced* because they can be produced with any fork, no matter what its period. Sounding boards in pianos and other stringed instruments act precisely as does the table top in this experiment; that is, they are set into forced vibrations by any note of the instrument and reënforce it accordingly.

396. Beats. Since two sound waves are able to unite so as to reënforce each other, it ought also to be possible to make them unite so as to interfere with or destroy each other. In other words, under the proper conditions *the union of two sounds ought to produce silence.*

Let two mounted tuning forks of the same pitch be set side by side, as in Fig. 352. Let the two forks be struck in quick succession with a soft mallet, for example, a rubber stopper on the end of a rod. The two notes will blend and produce a smooth, even tone. Then let a piece of wax or a small coin be stuck to a prong of one of the forks. This diminishes slightly the number of vibrations which this fork makes per second, since it increases its mass. Again, let the two forks be sounded together. The former smooth tone will be replaced by a throbbing or pulsating one. This is due to the alternate destruction and reënforcement of the sounds produced by the two forks. This pulsation is called the phenomenon of *beats.*

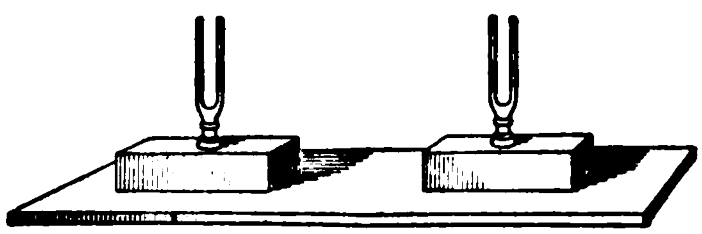


FIG. 352. Arrangement of forks for beats

The mechanism of the alternate destruction and reënforcement may be understood from the following. Suppose that one fork makes 256 vibrations per second (see the dotted line *AC* in Fig. 353), while the other makes 255 (see the heavy line *AC*). If at the beginning of a given second the two forks

are swinging *together*, so that they simultaneously send out condensations to the observer, these condensations will of course unite so as to produce a double effect upon the ear (see A', Fig. 353). Since now one fork gains one complete vibration per second over the other, at the end of the second considered the two forks will again be vibrating together, that is, sending out condensations which add their effects as before (see C'). In the middle of this second, however, the two forks are vibrating in opposite directions (see B); that is, one is sending out rarefactions while the other sends out condensations. At the ear of the observer the union of the rarefaction (backward motion of the air particles) produced by one fork with the condensation (forward motion) produced by the other results in no motion at all, provided the two motions have the same energy; that is, *in the middle of the second the two sounds have united to produce silence* (see B'). It will be seen from the above that *the number of beats per second is equal to the difference in the vibration numbers of the two forks.*

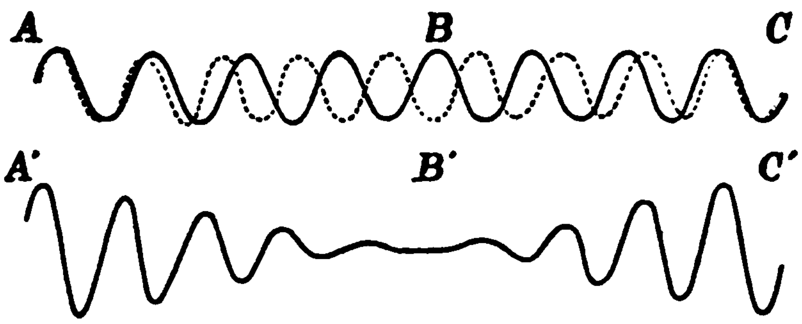


FIG. 353. Graphical illustration of beats

To test this conclusion, let more wax or a heavier coin be added to the weighted prong; the number of beats per second will be increased. Diminishing the weight will reduce the number of beats per second.

In tuning a piano the double and triple strings are brought into unison by tuning so as to eliminate beats.

397. Interference of sound waves by reflection. Let a thin cork about an inch in diameter be attached to one end of a brass rod from one to two meters long. Let this rod be clamped firmly in the middle, as in Fig. 354. Let a piece of glass tubing a meter or more long and from an inch to an inch and a half in diameter be slipped over the cork, as shown. Let the end of the rod be stroked longitudinally with a well-resined cloth. A loud, shrill note will be produced.

This note is due to the fact that the slipping of the resined cloth over the surface of the rod sets the latter into longitudinal vibrations, so that its ends impart alternate condensations and rarefactions to the layers of air in contact with them. As soon as this note is started

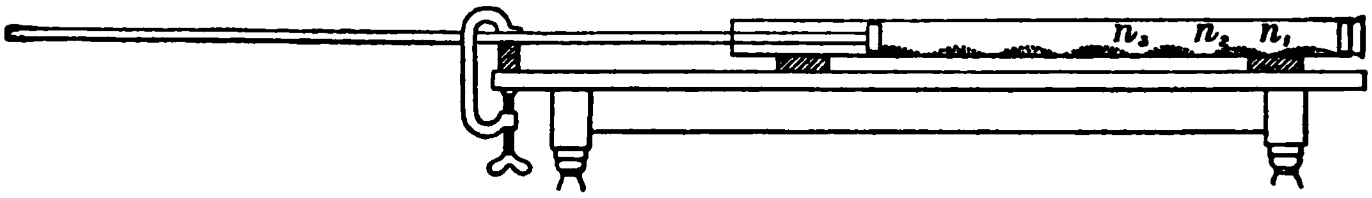


FIG. 354. Interference of advancing and retreating trains of sound waves

the cork dust inside the tube will be seen to be intensely agitated. If the effect is not marked at first, a slight slipping of the glass tube forward or back will bring it out. Upon examination it will be seen that the agitation of the cork dust is not uniform, but at regular intervals throughout the tube there will be regions of complete rest, n_1, n_2, n_3, etc., separated by regions of intense motion.

The points of rest correspond to the positions in which the reflected train of sound waves returning from the end of the tube neutralizes the effect of the advancing train passing down the tube from the vibrating rod. The points of rest are called *nodes*, the intermediate portions *loops* or *antinodes*. The distance between these nodes is one-half wave length, for

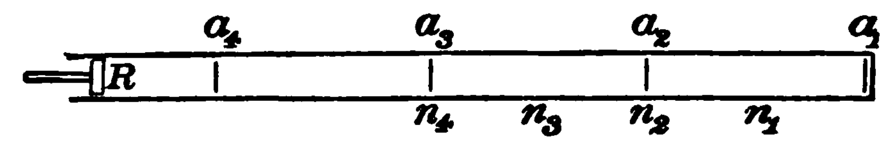


FIG. 355. Distance between nodes is one-half wave length

at the instant that the first wave front a_1 (Fig. 355) reaches the end of the tube it is reflected and starts back toward *R*. Since at this instant the second wave front a_2 is just one wave length to the left of a_1, the two wave fronts must meet each other at a point n_1, just one-half wave length from the end of the tube. The exactly equal and opposite motions of the particles in the two wave fronts exactly neutralize each other. Hence the point n_1 is a point of no motion, that is, a node. Again, at the instant that the reflected wave front a_1 met the advancing wave front a_2 at n_1, the third wave front a_3 was just one wave length to the left of n_1. Hence, as the first wave front a_1 continues

to travel back toward R it meets a_8 at n_2, just one-half wave length from n_1, and produces there a second node. Similarly, a third node is produced at n_3, one-half wave length to the left of n_2, etc. Thus *the distance between two nodes must always be just one half the wave length of the waves in the train.*

In the preceding discussion it has been tacitly assumed that the two oppositely moving waves are able to pass through each other without either of them being modified by the presence of the other. That two opposite motions are, in fact, transferred in just this manner through a medium consisting of elastic particles may be beautifully shown by the following experiment with the row of balls used in § 380.

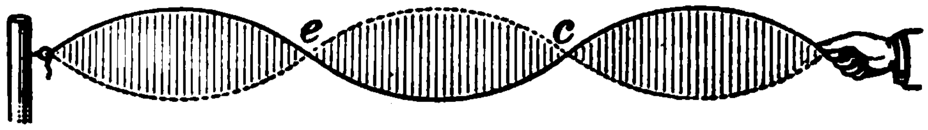


FIG. 356. Nodes and loops in a cord

Black line denotes advancing train ; dotted line, reflected train

Let the ball at one end of the row be raised a distance of, say, 2 inches and the ball at the other end raised a distance of 4 inches. Then let both balls be dropped simultaneously against the row. The two opposite motions will pass through each other in the row altogether without modification, the larger motion appearing at the end opposite to that at which it started, and the smaller likewise.

Another and more complete analogy to the condition existing within the tube of Fig. 354 may be had by simply vibrating one end of a two- or three-meter rope, as in Fig. 356. The trains of advancing and reflected waves which continuously travel through each other up and down the rope will unite so as to form a series of nodes and loops. The nodes at c and e are the points at which the advancing and reflected waves are always urging the cord equally in opposite directions. The distance between them is one half the wave length of the train sent down the rope by the hand.

QUESTIONS AND PROBLEMS

1. Account for the sound produced by blowing across the mouth of an empty bottle. The bottle may be tuned to different pitches by adding more or less water. Explain.

2. Explain the roaring sound heard when a sea shell, a tumbler, or an empty tin can is held to the ear.

3. Find the number of vibrations per second of a fork which produces resonance in a closed pipe 1 ft. long; in an open pipe 1 ft. long. (Take the speed of sound as 1120 ft. per second.)

4. A gunner hears an echo $5\frac{1}{2}$ sec. after he fires. How far away was the reflecting surface, the temperature of the air being 20° C.?

5. The shortest closed air column that gave resonance with a tuning fork was 32 cm. Find the rate of the fork if the velocity of sound was 340 meters per second.

6. A tuning fork gives strong resonance when held on its flat side or on its edge, but when held cornerwise over the air column the resonance ceases. Explain.

7. What is meant by the phenomenon of beats in sound? How may it be produced, and what is its cause?

8. What is the length of the shortest closed tube that will act as a resonator to a fork whose rate is 427 per second? (Temperature = 20° C.)

9. A fork making 500 vibrations per second is found to produce resonance in an air column like that shown in Fig. 349, first when the water is a certain distance from the top, and again when it is 34 cm. lower. Find the velocity of sound.

10. Show why an open pipe needs to be twice as long as a closed pipe if it is to respond to the same note.

CHAPTER XVII

PROPERTIES OF MUSICAL SOUNDS

Musical Scales

398. Physical basis of musical intervals. Let a metal or cardboard disk 10 or 12 inches in diameter be provided with four concentric rows of equidistant holes, the successive rows containing respectively 24, 30, 36, and 48 holes (Fig. 357). The holes should be about $\frac{1}{4}$ inch in diameter, and the rows should be about $\frac{1}{2}$ inch apart. Let this disk (a siren) be placed in the rotating apparatus and a constant speed imparted. Then let a jet of air be directed, as in § 385, against each row of holes in succession. It will be found that the musical sequence *do, mi, sol, do′* results. If the speed of rotation is increased, each note will rise in pitch, but the sequence will remain unchanged.

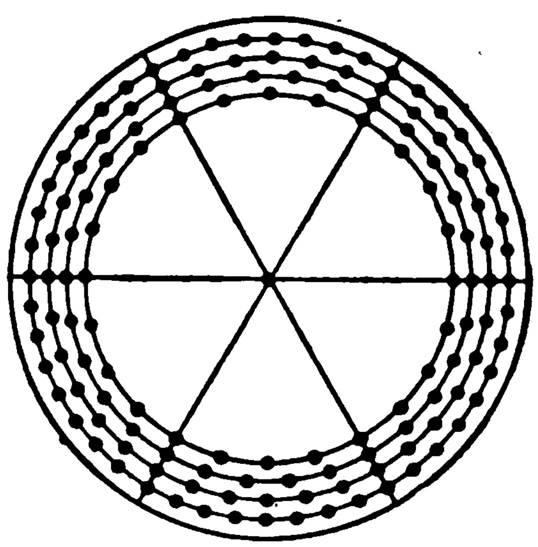


Fig. 357. Siren for producing musical sequence *do, mi, sol, do′*

We learn, therefore, that *the musical sequence do, mi, sol, do′ consists of notes whose vibration numbers have the ratios of* 24, 30, 36, *and* 48, *that is*, 4, 5, 6, 8, *and that this sequence is independent of the absolute vibration numbers of the tones.*

Furthermore, when two notes an octave apart are sounded together, they form the most harmonious combination which it is possible to obtain. These characteristics of notes an octave apart were recognized in the earliest times, long before anything whatever was known about the ratio of their vibration numbers. The preceding experiment showed that *this ratio is the simplest possible*, namely, 24 to 48, or 1 to 2. Again, the next easiest musical interval to produce, and the next

most harmonious combination which can be found, corresponds to the two notes commonly designated as *do*, *sol*. Our experiment showed that this interval corresponds to the next simplest possible vibration ratio, namely, 24 to 36, or 2 to 3. When *sol* is sounded with *do′*, the vibration ratio is seen to be 36 to 48, or 3 to 4. We see, therefore, that the three simplest possible ratios of vibration numbers, namely, 1 to 2, 2 to 3, and 3 to 4, are used in the production of the three notes *do*, *sol*, *do′*. Again, our experiment shows that another harmonious musical interval, *do*, *mi*, corresponds to the vibration ratio 24 to 30, or 4 to 5. We learn, therefore, that *harmonious musical intervals correspond to very simple vibration ratios.*

399. The major diatonic scale. When the three notes *do*, *mi*, *sol*, which, as seen above, have the vibration ratios 4, 5, 6, are all sounded together, they form a remarkably pleasing combination of tones. This combination was picked out and used very early in the musical development of the race. It is now known as the *major chord*. *The major diatonic scale is built up of three major chords* in the manner shown in the following table, where the first major chord is denoted by *1*, the second by *2*, and the third by *3*.

Syllables	*do*	*re*	*mi*	*fa*	*sol*	*la*	*si*	*do*	*re*
Letters	*C*	*D*	*E*	*F*	*G*	*A*	*B*	*C′*	*D′*
Relative vibration numbers	24	27	30	32	36	40	45	48	54
	1		*1*		*1*				
					2		*2*		*2*
				3		*3*		*3*	

The chords *do-mi-sol* (the tonic), *sol-si-re* (the dominant), and *fa-la-do* (the subdominant) occur frequently in all music.

Standard middle *C* forks made for physical laboratories all have the vibration number 256, which makes *A* in the physical scale $426\frac{2}{3}$. In the so-called *international pitch A* has 435 vibrations, and in the widely adopted American Federation of Musicians' pitch, 440.

400. The even-tempered scale. If G is taken as *do*, and a scale built up as above, it will be found that six of the above notes in each octave can be used in this new key, but that two additional ones are required (see table below). Similarly, to build up scales, as above, in all the keys demanded by modern music would require about fifty notes in each octave. Hence a compromise is made by dividing the octave into twelve equal intervals represented by the eight white and five black keys of a piano. How much this so-called *even-tempered scale* differs from the ideal, or diatonic, scale is shown below.

Note	*C*	*D*	*E*	*F*	*G*	*A*	*B*	*C′*	*D′*	*E′*	*F′*	*G′*
Diatonic	256	288	320	341⅓	384	426⅔	480	512	576	640	682.2	768
Diatonic key of *G*					384	432	480	512	576	640	720	768
Tempered . . .	256	287.4	322.7	341.7	383.8	430.7	483.5	512	574.8	645.4	683.4	767.6

VIBRATING STRINGS*

401. Laws of vibrating strings. Let two piano wires be stretched over a box or a board with pulleys attached so as to form a sonometer (Fig. 358). Let the weights A and B be adjusted until the two wires emit exactly the same note. The phenomenon of beats will make it possible to do this with great accuracy. Then let the bridge D be inserted exactly at the middle of one of the wires, and the two wires plucked in succession. The interval will be recognized at once as *do, do′*. Next let the bridge be inserted so as to make one wire two thirds as long as the other, and let the two be plucked again. The interval will be recognized as *do, sol*.

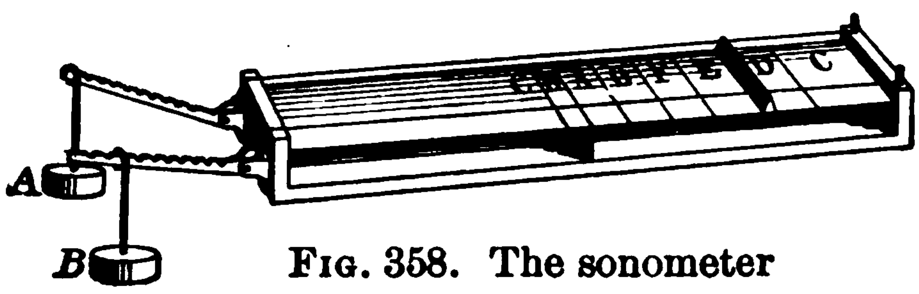


FIG. 358. The sonometer

Now it was shown in § 398 that *do′* has twice as many vibrations per second as *do*, and *sol* has three halves as many. Hence, since the length corresponding to *do′* is one half as great as the first length, and that corresponding to *sol* two thirds

*This discussion should be followed by a laboratory experiment on the laws of vibrating strings. See, for example, Experiment 41 of the authors' Manual.

as great, we conclude from this experiment that, other things being equal, *the vibration numbers of strings are inversely proportional to their lengths.*

Again, let the two wires be tuned to unison, and then let the weight *A* be increased until the pull which it exerts on the wire is exactly four times as great as that exerted by *B*. The note given out by the *A* wire will again be found to be an octave above that given out by the *B* wire.

We learn, then, that *the vibration numbers of similar strings of equal length are proportional to the square roots of their tensions.*

In stringed instruments, for example the piano, the different pitches are obtained by using strings of different length, tension, and mass per unit length.

402. Nodes and loops in vibrating strings. Let a string a meter long be attached to one of the prongs of a large tuning fork which makes in the neighborhood of 100 vibrations per second. Let the other end be attached as in the figure and the fork set into vibration. If the fork is not electrically driven, which is much to be preferred, it may be bowed with a violin bow or struck with a soft mallet. By making the tension of the thread, for example, proportional to the numbers 9, 4, and 1 it will be found possible to make it vibrate either as a whole, as in Fig. 359, or in two or three parts (Fig. 360).

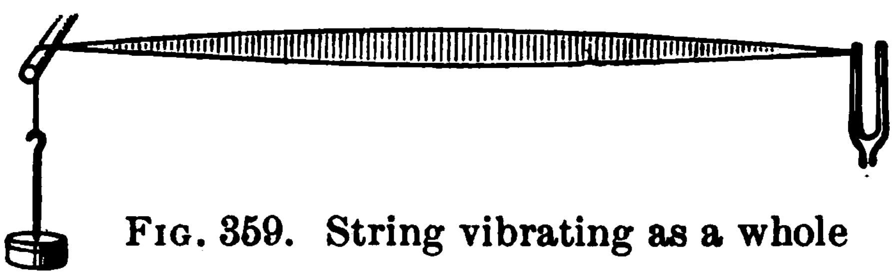


FIG. 359. String vibrating as a whole

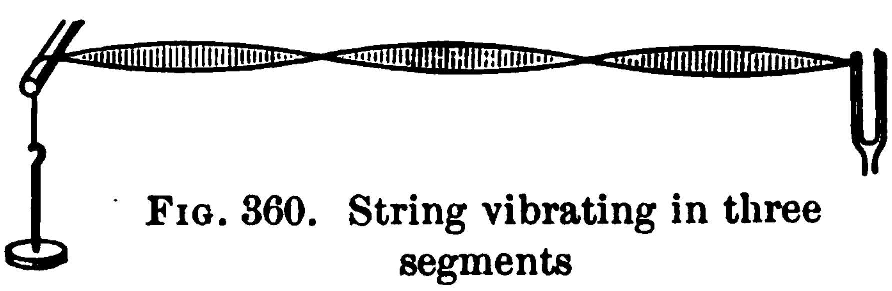


FIG. 360. String vibrating in three segments

This effect is due, as explained in § 397, to the interference of the direct and reflected waves sent down the string from the vibrating fork. But we shall show in the next paragraph that in considering the effects of the vibrating string on the surrounding air we shall make no mistake if we think of it as clamped at each node, and as actually vibrating in two or three or four separate parts, as the case may be.

Fundamentals and Overtones

403. Fundamentals and overtones. If the assertion just made be correct, then a string which has a node in the middle communicates to the air twice as many pulses per second as the same string when it vibrates as a whole. This may be conclusively shown as follows:

Let the sonometer wire (Fig. 358) be plucked in the middle and the pitch of the corresponding tone carefully noted. Then let the finger be touched to the middle of the wire, and the latter plucked midway between this point and the end.* The octave of the original note will be distinctly heard. Next let the finger be touched at a point one third of the wire length from one end, and the wire again plucked. The note will be recognized as *sol′*. Since we learned in § 399 that *sol′* has three halves as many vibrations as *do′*, it must have three times as many vibrations as the original note. Hence a wire which is vibrating in three segments sends out three times as many vibrations as when it is vibrating as a whole.

When a wire vibrates simply as a whole, it gives forth the lowest note which it is capable of producing. This note is called the *fundamental* or first partial of the wire. When the wire is made to vibrate in two parts, it gives forth, as has just been shown, a note an octave higher than the fundamental. This is called the *first overtone* or second partial. When the wire is made to vibrate in three parts it gives forth a note corresponding to three times the vibration number of the fundamental, namely, *sol′*. This is called the *second overtone* or third partial. When the wire vibrates in four parts, it gives forth the third overtone, which is two octaves above the fundamental. The overtones of wires are often called *harmonics*. They bear the vibration ratios 2, 3, 4, 5, 6, 7, etc. to the fundamental.†

* It is well to remove the finger almost simultaneously with the plucking.

† Some instruments, such as bells, can produce higher tones whose vibration numbers are not exact multiples of the fundamental. These notes are still called overtones, but they are not called harmonics, the latter term being reserved for the multiples. Strings produce harmonics only.

404. Simultaneous production of fundamentals and overtones. Thus far we have produced overtones only by forcing the wire to remain at rest at properly chosen points during the bowing.

Now let the wire be plucked at a point one fourth of its length from one end, *without being touched in the middle.* The tone most distinctly heard will be the fundamental; but if the wire is now touched very lightly exactly in the middle, the sound, instead of ceasing altogether, will continue, but the note heard will be an octave higher than the fundamental, showing that in this case there was superposed upon the vibration of the wire as a whole a vibration in two segments also (Fig. 361). By touching the wire in the middle the vibration as a whole was destroyed, but that in two parts remained. Let the experiment be repeated, with this difference, that the wire is now plucked in the middle instead of one fourth its length from one end. If it is now touched in the middle, the sound will entirely cease, showing that when a wire is plucked in the middle there is no first overtone superposed upon the fundamental. Let the wire be plucked again one fourth of its length from one end and careful attention given to the compound note emitted. It will be found possible to recognize both the fundamental and the first overtone sounding at the same time. Similarly, by plucking at a point one sixth of the length of the wire from one end, and then touching it at a point one third of its length from the end, the second overtone may be made to appear distinctly, and a trained ear will detect it in the note given off by the wire, even before the fundamental is suppressed by touching at the point indicated.

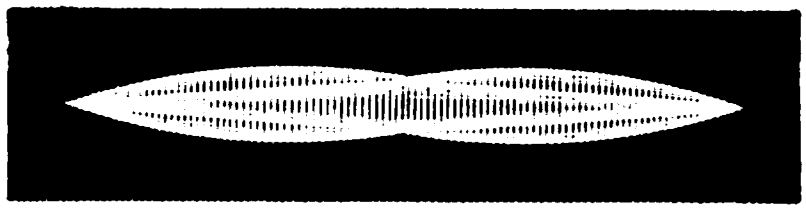


FIG. 361. A wire simultaneously emitting its fundamental and first overtone

The experiments show, therefore, that in general *the note emitted by a string plucked at random is a complex one, consisting of a fundamental and several overtones, and that just what overtones are present in a given case depends on where and how the wire is plucked.*

405. Quality. Let the sonometer wire be plucked first in the middle and then close to one end. The two notes emitted will have exactly the same pitch, and they may have exactly the same loudness,

but they will be easily recognized as different in respect to something which we call *quality*. The experiment of the last paragraph shows that the real physical difference in the tones is a difference in the sorts of overtones which are mixed with the fundamental in the two cases.

Again, let a mounted *C′* fork be sounded simultaneously with a mounted *C* fork. The resultant tone will sound like a rich, full *C*, which will change into a hollow *C* when the *C′* is quenched with the hand.

Everyone is familiar with the fact that when notes of the same pitch and loudness are sounded upon a piano, a violin, and a cornet, the three tones can be readily distinguished. The last experiments suggest that the cause of this difference lies in the fact that it is only the *fundamental* which is the same in the three cases, while the *overtones* are different. In other words, the characteristic of a tone which we call its quality is determined simply by *the number and prominence of the overtones which are present.* If the overtones present are few and weak, while the fundamental is strong, the tone is, as a rule, soft and mellow, as when a sonometer wire is plucked in the middle, or a closed organ pipe is blown gently, or a tuning fork is struck with a soft mallet. The presence of comparatively strong overtones up to the fifth adds fullness and richness to the resultant tone. This is illustrated by the ordinary tone from a piano, in which several if not all of the first five overtones have a prominent place. When overtones higher than the sixth are present, a sharp metallic quality begins to appear. This is illustrated when a tuning fork is struck, or a wire plucked, with a hard body. It is in order to avoid this quality that the hammers which strike against piano wires are covered with felt.

406. Analysis of tones by the manometric flame. A very simple and beautiful way of showing the complex character of most tones is furnished by the so-called *manometric flames.* This device consists of the following parts: a chamber in the block *B* (Fig. 362), through which gas is led by way of the

tubes C and D to the flame F; a second chamber in the block A, separated from the first chamber by an elastic diaphragm made of very thin sheet rubber or paper, and communicating with the source of sound through the tube E and trumpet G; and a rotating mirror M by which the flame is observed. When a note is produced before the mouthpiece G, the vibrations of the diaphragm produce variations in the pressure of

FIG. 362. Analysis of sounds with manometric flames

the gas coming to the flame through the chamber in B, so that when condensations strike the diaphragm the height of the flame is increased, and when rarefactions strike it the height of the flame is diminished. If these up-and-down motions of the flame are viewed in a rotating mirror, the longer and shorter images of the flame, which correspond to successive intervals of time, appear side by side, as in Fig. 363. If a rotating mirror is not to be had, a piece of ordinary mirror glass held in the hand and oscillated back and forth about a vertical axis will be found to give satisfactory results.

First let the mirror be rotated when no note is sounded before the mouthpiece. There will be no fluctuations in the flame, and its image, as seen in the moving mirror, will be a straight band, as shown in *2* (Fig. 363). Next let a mounted *C* fork be sounded, or some other simple tone produced in front of *G*. The image in the mirror will be that shown in *3*. Then let another fork, *C'*, be sounded in place of the *C*. The image will be that shown in *4*. The images of the flame are now twice as close together as before, since the blows strike the diaphragm twice as often. Next let the open ends of the resonance boxes of the tuning forks *C* and *C'* be held together in front of *G*. The image of the flame will be as shown in *5*. If the vowel *o* be sung in the pitch *B*♭ before the mouthpiece, a figure exactly similar to *5* will be produced, thus showing that this last note is a complex, consisting of a fundamental and its first overtone.

Fig. 363. Vibration forms shown by manometric flames

The proof that most other tones are likewise complex lies in the fact that when analyzed by the manometric flame they show figures not like *3* and *4*, which correspond to simple tones, but like *5*, *6*, and *7*, which may be produced by sounding combinations of simple tones. In the figure, *6* is produced by singing the vowel *e* on C''; *7* is obtained when *o* is sung on C''. The beautiful photographs opposite page 346, taken by Prof. D. C. Miller, show the extraordinary complexity of spoken words.

407. Helmholtz's experiment. If the loud pedal on a piano is held down and the vowel sounds *o͞o*, *ī*, *ā*, *ah*, *ē* sung loudly into the strings, these vowels will be caught up and returned by the instrument with sufficient fidelity to make the effect almost uncanny.

It was by a method which may be considered as merely a refinement of this experiment that Helmholtz proved conclusively that quality is determined simply by the number and

prominence of the overtones which are blended with the fundamental. He first constructed a large number of resonators, like that shown in Fig. 364, each of which would respond to a note of some particular pitch. By holding these resonators in succession to his ear while a musical note was sounding, he picked out the constituents of the note; that is, he found out just what overtones were present and what were their relative intensities. Then he put these constituents together and reproduced the original tone. This was done by sounding simultaneously, with appropriate loudness, two or more of a whole series of tuning forks which had the vibration ratios 1, 2, 3, 4, 5, 6, 7. In this way he succeeded not only in imitating the qualities of different musical instruments but even in reproducing the various vowel sounds.

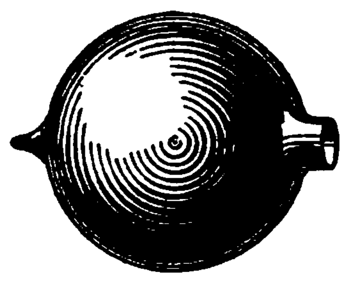


FIG. 364. Helmholtz's resonator

408. Sympathetic vibrations. Let two mounted tuning forks of the same pitch be placed with the open ends of their resonators facing each other. Let one be set into vigorous vibration with a soft mallet and then quickly quenched by grasping the prongs with the hand. The other fork will be found to be sounding loudly enough to be heard over a large room. Next let a penny be waxed to one prong of the second fork and the experiment repeated. When the sound of the first fork is quenched, no sound whatever will be found to be coming from the second fork.

The experiment illustrates the phenomenon of *sympathetic vibrations*, and shows what conditions are essential to its appearance. If two bodies capable of emitting musical notes have exactly the same natural period of vibration, the pulses communicated to the air when one alone is sounding beat upon the second at intervals which correspond exactly to its own natural period. Each pulse, therefore, adds its effect to that of the preceding pulses; and though the effect due to a single pulse is very slight, a great number of such pulses produce a

Sound Waves of Spoken Words

Sound waves corresponding to spoken words, from a photograph by Professor D. C. Miller. The words were spoken by a barytone voice (Professor Miller's) having a normal pitch of from 150 to 180, varying with the inflection. The sound waves cause vibrations in a diaphragm. These vibrations are transferred to a very small mirror, which reflects a beam of light to a moving photographic film

Sound Ranging Record of the End of the War

'ervice and illustrates the method developed during the World
of the sound wave caused by the explosion of the gun. Sound
ile or so apart were electrically connected to a central station
l om the differences in these times of
sl ı in the figure) the position of a gun
re ds of enemy guns were located and
c uproar of guns at 58 minutes 59 seconds after 10 o'clock, but at
o'clock, there is almost complete silence of artillery

large resultant effect. In the same way a large number of very feeble pulls may set a heavy pendulum into vibrations of considerable amplitude if the pulls come at intervals exactly equal to the natural period of the pendulum. On the other hand, if the two sounding bodies have even a slight difference of period, the effect of the first pulses is neutralized by the effect of succeeding pulses as soon as the two bodies, on account of their difference in period, get to swinging in opposite directions.

Let notes of different pitches be sung into a piano when the dampers are lifted. The wire which has the pitch of the note sounded will in every case respond. Sing a little off the key and the response will cease.

409. Sympathetic vibrations produced by overtones. It is not essential, in order that a body may be set into sympathetic vibrations, that it have the same pitch as the sounding body, provided its pitch corresponds exactly with the pitch of one of the *overtones* of that body.

Thus, if the damper is lifted from the C string of a piano and the octave below, C_1, is sounded loudly, C will be heard to sound after C_1 has been quenched by the damper. In this case it is the first overtone of C_1 which is in exact tune with C, and which therefore sets it into sympathetic vibration. Again, if the damper is lifted from the G string while C_1 is sounded, this note will be found to be set into vibration by the second overtone of C_1. A still more interesting case is obtained by removing the damper from E while C_1 is sounded. When C_1 is quenched, the note which is heard is not E, but an octave above E; that is, E'. This is because there is no overtone of C_1 which corresponds to the vibration of E; but the fourth overtone of C_1, which has five times the vibration number of C_1, corresponds exactly to the vibration number of E', the first overtone of E. Hence E is set into vibration not as a whole but in halves.

410. Physical significance of harmony and of discord. Let two pieces of glass tubing about an inch in diameter and a foot and a half long be supported vertically, as shown in Fig. 365. Let two gas jets (made by drawing down pieces of one-fourth inch glass tubing until, with full gas pressure, the flame is about an inch long) be thrust inside these tubes to a height of about three or four inches from the bottom. Let

the gas be turned down until the tubes begin to sing. Without attempting to discuss the part which the flame plays in the production of the sound, we wish simply to call attention to the fact that the two tones are either quite in unison or so near it that only a few beats are produced per second. Now let the length of one of the tubes be slightly increased by slipping the paper cylinder S up over its end. The number of beats will be rapidly increased until they will become indistinguishable as separate beats and will merge into a jarring, grating discord.

FIG. 365. Illustrating the production of discords

The experiment teaches that *discord is simply a phenomenon of beats.* If the vibration numbers do not differ by more than five or six, that is, if there are not more than five or six beats per second, the effect is not particularly unpleasant. From this point on, however, as the difference in the vibration numbers, and therefore in the number of beats per second, increases, the unpleasantness increases, and becomes worst at a difference of about thirty. Thus, the notes B and C', which differ by about thirty-two beats per second, produce about the worst possible discord. When the vibration numbers differ by as much as seventy, which is about the difference between C and E, the effect is again pleasing, or harmonious. Moreover, in order that two notes may harmonize well, it is necessary not only that the notes themselves shall not produce an unpleasant number of beats, but also that such beats shall not arise from their overtones. Thus, C and B are very discordant, although they differ by a large number of vibrations per second. The discord in this case arises between B and C', the first overtone of C.

Again, there are certain classes of instruments, of which bells are a striking example, which produce insufferable discords when even such notes as *do*, *sol*, *do'*, are sounded simultaneously

upon them. This is because these instruments, unlike strings and pipes, have overtones which are not harmonics, that is, which are not multiples of the fundamental; and these overtones produce beats either among themselves or with one of the fundamentals. It is for this reason that in playing chimes the bells are struck in succession, not simultaneously.

QUESTIONS AND PROBLEMS

1. In what three ways do piano makers obtain the different pitches?

2. What did Helmholtz prove by means of his resonators?

3. If middle C is struck on a piano while the key for G in the octave above is held down, G will be distinctly heard when C is silenced. Explain.

4. At what point must the G_1 string be pressed by the finger of the violinist in order to produce the note C?

5. If one wire has twice the length of another and is stretched by four times the stretching force, how will their vibration numbers compare?

6. A wire gives out the note G. What is its fourth overtone?

7. If middle C had 300 vibrations per second, how many vibrations would F and A have?

8. What is the fourth overtone of C? the fifth overtone?

9. There are seven octaves and two notes on an ordinary piano, the lowest note being A_4 and the highest one C''''. If the vibration number of the lowest note is 27, find the vibration number of the highest.

10. Find the wave length of the lowest note on the piano; the wave length of the highest note. (Take the speed of sound as 1130 ft. per sec.)

11. A violin string is commonly bowed about one seventh of its length from one end. Why is this better than bowing in the middle?

12. Build up a diatonic scale on $C = 264$.

WIND INSTRUMENTS

411. Fundamentals of closed pipes. Let a tightly fitting rubber stopper be inserted in a glass tube *a* (Fig. 366), eight or ten inches long and about three fourths of an inch in diameter. Let the stopper be pushed along the tube until, when a vibrating C' fork is held before the mouth, resonance is obtained as in § 391. (The length will be six or seven inches.) Then let the fork be removed and a stream of air blown

across the mouth of the tube through a piece of tubing *b*, flattened at one end as in the figure.* The pipe will be found to emit strongly the note of the fork.

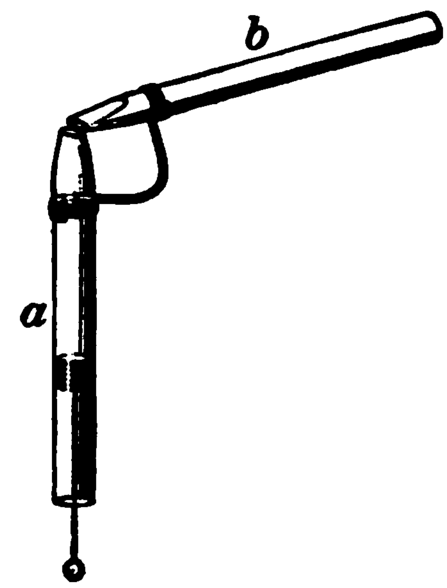


FIG. 366. Musical notes from pipes

In every case it is found that a note which a pipe may be made to emit is always a note to which it is able to respond when used as a resonator. Since, in § 392, the best resonance was found when the wave length given out by the fork was four times the length of the pipe, we learn that *when a current of air is suitably directed across the mouth of a closed pipe, it will emit a note which has a wave length four times the length of the pipe.* This note is called the *fundamental* of the pipe. It is the lowest note which the pipe can be made to produce.

412. Fundamentals of open pipes. Since we found in § 393 that the lowest note to which a pipe open at the lower end can respond is one the wave length of which is twice the pipe length, we infer that an open pipe, when suitably blown, ought to *emit* a note the wave length of which is twice the pipe length. This means that if the same pipe is blown first when closed at the lower end and then when open, the first note ought to be an octave lower than the second.

Let the pipe *a* (Fig. 366) be closed at the bottom with the hand and blown; then let the hand be removed and the operation repeated. The second note will indeed be found to be an octave higher than the first.

We learn, therefore, that *the fundamental of an open pipe has a wave length equal to twice the pipe length.*

413. Overtones in pipes. It was found in § 392 that there is a whole series of pipe lengths which respond to a given

* If the arrangement of Fig. 366 is not at hand, simply blow with the lips across the edge of a piece of ordinary glass tubing within which a rubber stopper may be pushed back and forth.

fork, and that these lengths bear to the wave length of the fork the ratios $\frac{1}{4}$, $\frac{3}{4}$, $\frac{5}{4}$, etc. This is equivalent to saying that a closed pipe of *fixed* length can respond to a whole series of notes whose vibration numbers have the ratios 1, 3, 5, 7, etc. Similarly, in § 393, we found that in the case of an open pipe the series of pipe lengths which will respond to a given fork bear to the wave length of the fork the ratios $\frac{1}{2}$, $\frac{2}{2}$, $\frac{3}{2}$, $\frac{4}{2}$, etc. This, again, is equivalent to saying that an open pipe can respond to a series of notes whose vibration numbers have the ratios 1, 2, 3, 4, 5, etc. Hence we infer that it ought to be possible to cause both open and closed pipes to emit notes of higher pitch than their fundamentals (that is, overtones), and that the first overtone of an *open* pipe should have twice the rate of vibration of the fundamental (that is, it should be *do'*, the fundamental being considered as *do*); that the second overtone should vibrate three times as fast as the fundamental (that is, it should be *sol'*); that the third overtone should vibrate four times as fast (that is, it should be *do''*); that the fourth overtone should vibrate five times as fast (that is, it should be *mi''*); etc. In the case of the *closed* pipe, however, the first overtone should have a vibration rate three times that of the fundamental (that is, it should be *sol'*); the second overtone should vibrate five times as fast (that is, it should be *mi''*); etc. In other words, while an open pipe ought to give forth *all* the harmonics, both odd and even, a closed pipe ought to produce the *odd* harmonics but be entirely incapable of producing the *even* ones.

Let the pipe of Fig. 366 be blown so as to produce the fundamental when the lower end is open. Then let the strength of the air blast be increased. The note will be found to spring to *do'*. By blowing still harder it will spring to *sol'*, and a still further increase will probably bring out *do''*. The odd and the even harmonics are, in fact, emitted by the open pipe, as our theory predicted. When the lower end is closed, however, the first overtone will be found to be *sol'*, and the next one *mi''*, just as our theory demands for the closed pipe.

414. Mechanism of emission of notes by pipes. Blowing across the mouth of a pipe produces a musical note, because the jet of air vibrates back and forth across the lip in a period which is determined wholly by the natural resonance period of the pipe. Thus, suppose that the jet *a* (Fig. 367) first strikes just inside the edge, or *lip*, of the pipe. A condensational pulse starts down the pipe. When it returns to the mouth after reflection at the closed end, it pushes the jet outside the lip. This starts a rarefaction down the pipe, which, after return from the lower end, pulls the jet in again. There are thus sent out into the room regularly timed puffs, the period of which is controlled by the reflected pulses coming back from the lower end, that is, by the natural resonance period of the pipe.

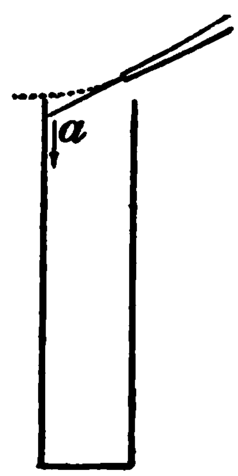


FIG. 367. Vibrating air jet

By blowing more violently it is possible to create, by virtue of the friction of the walls, so great and so sudden a compression in the mouth of the pipe that the jet is forced out over the edge before the return of the first reflected pulse. In this case no note will be produced unless the blowing is of just the right intensity to cause the jet to swing out in the period corresponding to an overtone. In this case the reflected pulses will return from the end at just the right intervals to keep the jet swinging in this period. This shows why a current of a particular intensity is required to start any particular overtone.

Another way of looking at the matter is to think of the pipe as being filled up with air until the pressure within it is great enough to force the jet outside the lip, upon which a period of discharge follows, to be succeeded in turn by another period of charge. These periods are controlled by the length of the pipe and the violence of the blowing, precisely as described above.

With open pipes the situation is in no way different save that the reflection of a condensation as a rarefaction at the lower end makes the natural period twice as high, since the pipe length is now one-half wave length instead of one-fourth wave length (see § 393).

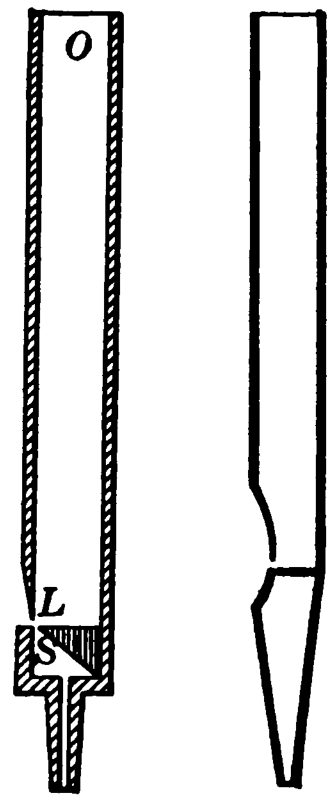


FIG. 368. Organ pipes

415. Vibrating air-jet instruments. The mechanism of the production of musical tones by the ordinary organ pipe, the flute, the fife, the piccolo, and all whistles is essentially the same as in the case of the pipe of Fig. 367. In all these instruments an air jet is made to play across the edge of an opening in an air chamber, and the reflected pulses returning from the other end of the chamber cause it to vibrate back and forth, first into the chamber and then out again. In this way a series of regularly timed puffs of air is made to pass from the instrument to the ear of the observer precisely as in the case of the rotating disk of § 385. The air chamber may be either open or closed at the remote end. In the flute it is open, in whistles it is usually closed, and in organ pipes it may be either open or closed. Fig. 368 shows a cross section of two types of organ pipes. The jet of air from S vibrates across the lip L in obedience to the pressure exerted on it by waves reflected from O. Pipe organs are provided with a different pipe for each note, but the flute, piccolo, and fife are made to produce a whole series of notes, either by blowing overtones or by opening holes in the tube, — an operation which is equivalent to cutting the tube off at the hole. Although important orchestral instruments, the flute and piccolo are not rich in overtones.

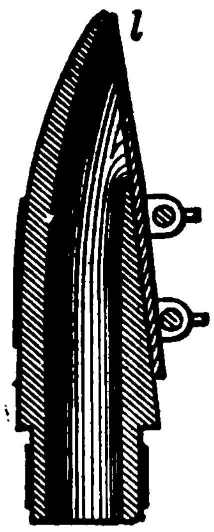


FIG. 369. Mouthpiece of a clarinet, showing the tongue l, which opens and closes the upper end of the pipe

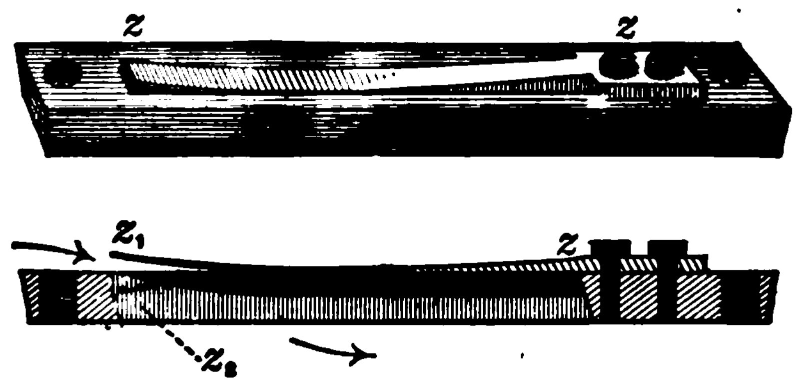


FIG. 370. The vibrating tongue of the mouth organ, accordion, etc.

416. Vibrating reed instruments. In reed instruments the vibrating air jet is replaced by a vibrating reed, or tongue, which opens and closes, at absolutely regular intervals, an opening against which the performer is directing a current of air. In the clarinet, the oboe, the bassoon, etc. the reed is placed at the upper end of the tube (see *l*, Fig. 369), and the theory of its opening and closing the orifice so as to admit successive puffs of air to the pipe is identical with the theory of the fluctuation of the air jet into and out of the organ pipe. For in these instruments the reed has little rigidity and its vibrations are controlled largely by the reflected pulses but partly by the reed and by the lips of the performer.

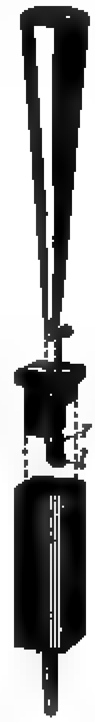


FIG. 371. The reed-organ pipe

In other reed instruments, like the mouth organ, the common reed organ, or the accordion, it is the elasticity of the reed alone (see *z*, Fig. 370) which controls the emission of pulses. In such instruments there is no necessity for air chambers. The arrows of Fig. 370 indicate the direction of the air current which is interrupted as the reed vibrates between the positions z_1 and z_2.

In still other reed instruments, like the reed pipes used in large organs (Fig. 371), the period of the pulses is controlled partly by the elasticity of the reed and partly by the return of the reflected waves; in other words, the natural period of the reed is more or less coerced by the period of the reflected pulses. Within certain limits, therefore, such instruments may be tuned by changing the length of the vibrating reed *l* without changing the length of the pipe. This is done by pushing the wire *r* up or down.

FIG. 372. The cornet

417. Vibrating lip instruments. In instruments of the bugle and cornet type the vibrating reed is replaced by the vibrating lips of the musician, the period of their vibration being controlled, precisely as in the organ pipe or the clarinet, by the period of the returning pulses. In the bugle the pipe length is fixed,

and because of the narrowness of the tube all bugle calls are played with overtones. In the cornet (Fig. 372) and in most forms of horns, valves *a*, *b*, *c*, worked by the fingers, vary the length of the pipe, and hence such instruments can produce as many series of fundamentals and overtones as there are possible tube lengths. In the trombone the variation of pitch is accomplished by blowing overtones and by changing the length of the tube by a sliding U-shaped portion

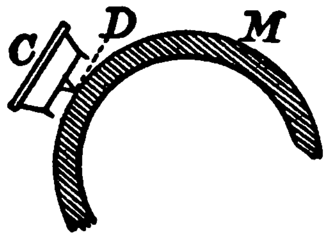


FIG. 373

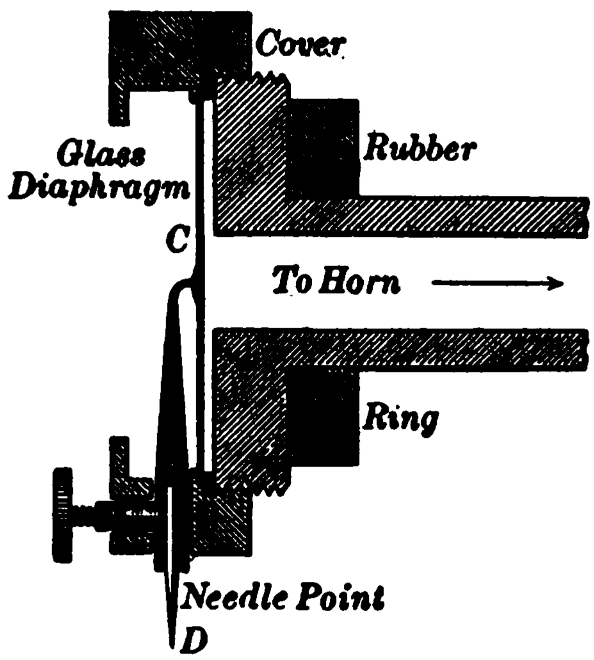


FIG. 374. Mechanism for forming gramophone records

418. The phonograph. In the original form of the phonograph the sound waves, collected by the cone, are carried to a thin metallic disk C (Fig. 373), exactly like a telephone diaphragm, which takes up very nearly the vibration form of the wave which strikes it. This vibration form is permanently impressed on the wax-coated cylinder M by means of a stylus D which is attached to the back of the disk. When the stylus is run a second time over the groove which it first made in the wax, it receives again and imparts to the disk the vibration form which first fell upon it. This is the principle of the

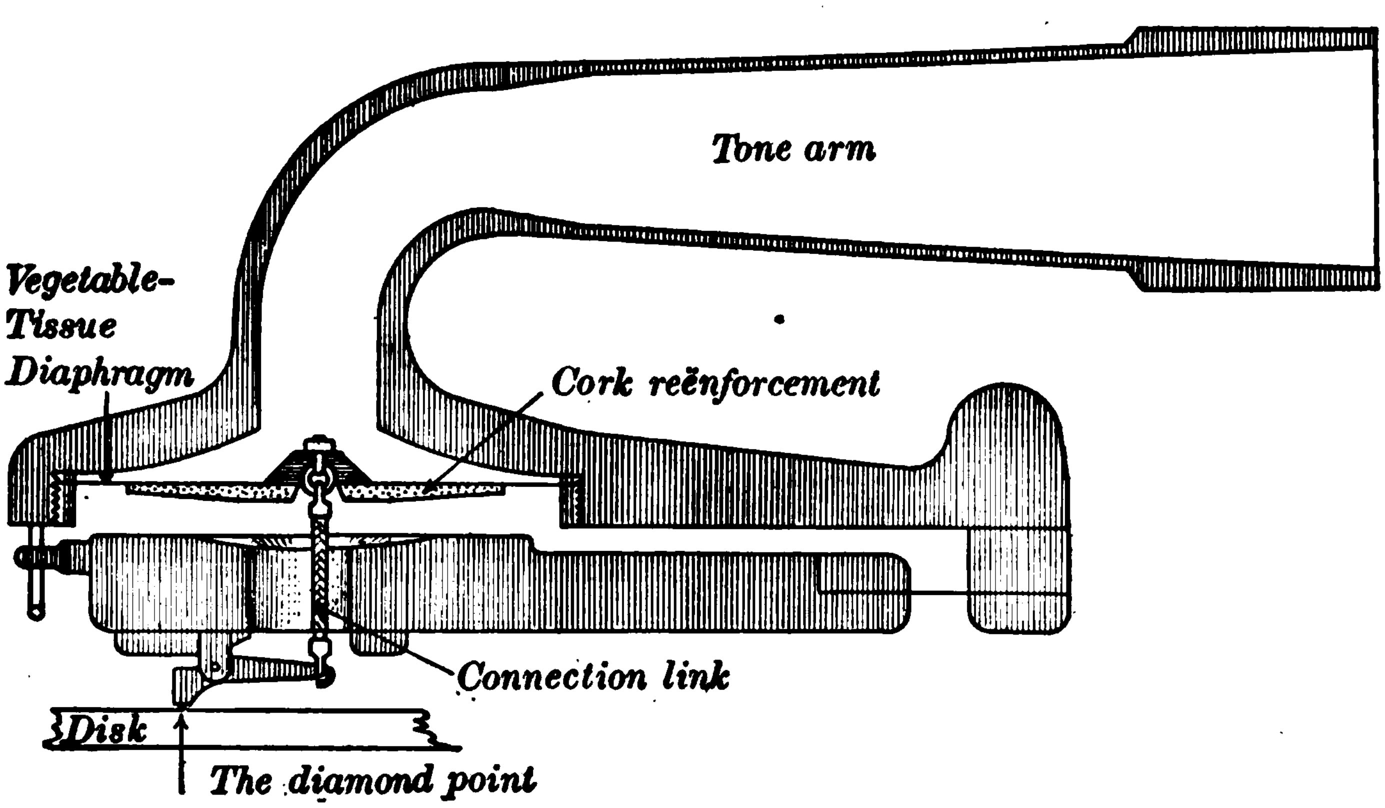


FIG. 375. The Edison diamond reproducer

dictaphone and the ediphone, used to replace stenographers in business offices. The typist writes the letter by listening to the reproduction of the dictation.

In the most familiar of the modern forms of the phonograph (gramophone, etc.) the needle point D, instead of digging a groove in wax, vibrates back and forth (see Fig. 374) over a greased zinc disk. This wavy trace in the disk is etched out with chromic acid. Then a copper mold is made by the electrotyping process, and as many as a thousand facsimiles of the original wavy line are impressed on hard-rubber disks by heat and pressure. When the needle is again run over the disk, it follows along the wavy groove and transmits to the diaphragm C vibrations exactly like those which originally fell upon it. Spoken words and vocal and orchestral music are reproduced in pitch, loudness, and quality with wonderful exactness. This instrument is one of the many inventions of Thomas Edison (see opposite p. 316). The diamond-tip reproducer used with the hill-and-dale Edison disks is shown in Fig. 375.

QUESTIONS AND PROBLEMS

1. What proves that a musical note is transmitted as a wave motion?

2. What evidence have you that sound waves are longitudinal vibrations?

3. Why is the pitch of a sound emitted by a phonograph raised by increasing the speed of rotation of the disk?

4. What will be the relative lengths of a series of organ pipes which produce the eight notes of a diatonic scale?

5. Will the pitch of a pipe organ be the same in summer as on a cold day in winter? What could cause a difference?

6. Explain how an instrument like the bugle, which has an air column of unchanging length, may be made to produce several notes of different pitch, such as C, G, C', E', G'. (C is not often used.)

7. Why is the quality of an open organ pipe different from that of a closed organ pipe?

8. The velocity of sound in hydrogen is about four times as great as it is in air. If a C pipe is blown with hydrogen, what will be the pitch of the note emitted?

9. What effect will be produced on a phonograph record made with the instrument of Fig. 374 if the loudness of a note is increased? if the pitch is lowered an octave?

CHAPTER XVIII

NATURE AND PROPAGATION OF LIGHT

TRANSMISSION OF LIGHT

419. Speed of light. Before the year 1675 light was thought to pass instantaneously from the source to the observer. In that year, however, Olaus Römer, a young Danish astronomer, made the following observations. He had observed accurately the instant at which one of Jupiter's satellites M (Fig. 376) passed into Jupiter's shadow when the earth was at E, and predicted, from the known mean time between such eclipses, the exact instant at which a given eclipse should occur six months later when the earth was at E'. It actually took place 16 minutes 36 seconds (996 seconds) later. He concluded that the 996 seconds' delay represented the time required for light to travel across the earth's orbit, a distance known to be about 180,000,000 miles. The most precise of modern determinations of the speed of light are made by laboratory methods. The generally accepted value, that of Michelson, of The University of Chicago, is 299,860 kilometers per second. It is sufficiently correct to remember it as 300,000 kilometers, or 186,000 miles.

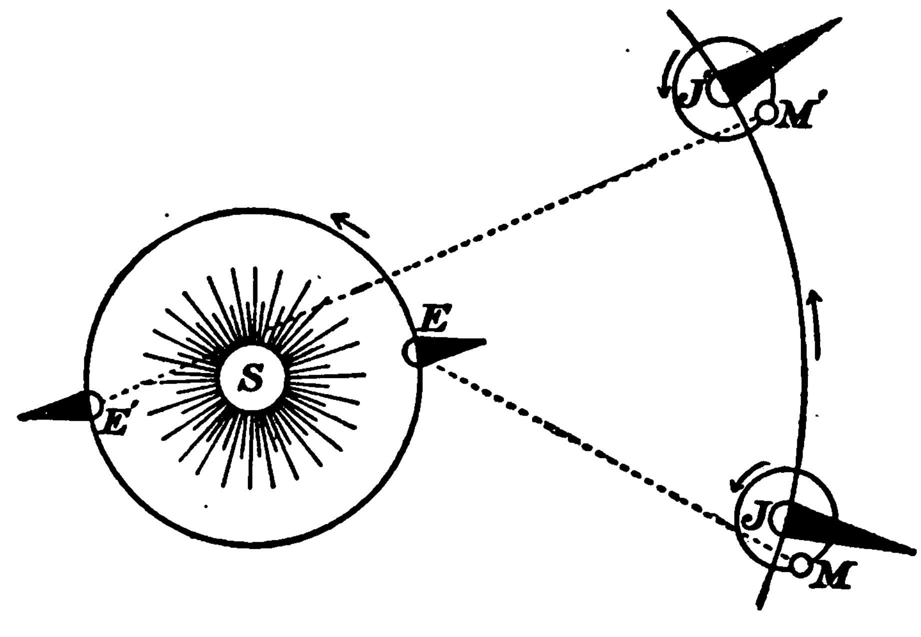


FIG. 376. Illustrating Römer's determination of the velocity of light

Though this speed would carry light around the earth $7\frac{1}{2}$ times in a second, yet it is so small in comparison with interstellar distances that the light which is now reaching the earth from the nearest fixed star, Alpha Centauri, started 4.4 years ago. If an observer on the pole star had a telescope powerful enough to enable him to see events on the earth, he would not have seen the battle of Gettysburg (which occurred in July, 1863) until January, 1918.

Both Foucault in France and Michelson in America have measured directly the velocity of light in water and have found it to be only three fourths as great as in air. It will be shown later that in all transparent liquids and solids it is less than it is in air.

420. Reflection of light.* Let a beam of sunlight be admitted to a darkened room through a narrow slit. The straight path of the beam will be rendered visible by the brightly illumined dust particles suspended in the air. Let the beam fall on the surface of a mirror. Its direction will be seen to be sharply changed, as shown in Fig. 377. Let the mirror be held so that it is perpendicular to the beam. The beam will be seen to be reflected directly back on itself. Let the mirror be turned through an angle of 45°. The reflected beam will move through 90°.

FIG. 377. Illustrating law of reflection of light

The experiment shows roughly, therefore, that the angle IOP, between the incident beam and the normal to the mirror, is equal to the angle POR, between the reflected beam and the normal to the mirror. The first angle, IOP, is called the angle of incidence, and the second, POR, the angle of reflection. *The angle of reflection is equal to the angle of incidence.*

* An exact laboratory experiment on the law of reflection should either precede or follow this discussion. See, for example, Experiment 42 of the authors' Manual.

A. A. MICHELSON, CHICAGO

Distinguished for extraordinarily accurate experimental researches in light. First American scientist to receive the Nobel prize

LORD RAYLEIGH (ENGLAND)

Distinguished for the discovery of argon, for very accurate determinations in electricity and sound and for profound theoretical studies

HENRY A. ROWLAND, JOHNS HOPKINS

Distinguished for the invention of the concave grating and for epoch-making studies in heat and electricity

SIR WILLIAM CROOKES, LONDON

Distinguished for his pioneer work (1875) in the study and interpretation of cathode rays (pp. 428 and 438)

A GROUP OF MODERN PHYSICISTS

X-Ray Picture of the Human Thorax

This figure is a remarkable picture of the human thorax with the apex of the heart showing clearly on the right of the spinal column and the base stretching across the column, part of it showing distinctly on the left side opposite the apex

421. Diffusion of light. In the last experiment the light was reflected by a very smooth plane surface. Now let the beam be allowed to fall upon a rough surface like that of a sheet of unglazed white paper. No reflected beam will be seen; but instead the whole room will be brightened appreciably, so that the outline of objects before invisible may be plainly distinguished.

The beam has evidently been scattered in all directions by the innumerable little reflecting surfaces of which the surface of the paper is composed. The effect will be much more noticeable if the beam is allowed to fall alternately on a piece of dead-black cloth and on the white paper.

Fig. 378. Regular and irregular reflection

The light is largely absorbed by the cloth, while it is scattered or *diffusely reflected* by the paper. Illumination sufficiently strong for sewing on white material may be altogether too weak for working on black goods. The difference between a smooth reflector and a rough one is illustrated in greatly magnified form in Fig. 378. The air shafts of apartment houses are made white to get the maximum diffusion of daylight into rooms that might otherwise be very dark.

422. Visibility of nonluminous bodies. Everyone is familiar with the fact that certain classes of bodies, such as the sun, a gas flame, etc., are self-luminous (that is, visible on their own account), while other bodies, like books, chairs, tables, etc., can be seen only when they are in the presence of luminous bodies. The above experiment shows how such nonluminous, diffusing bodies become visible in the presence of luminous bodies. For, since a diffusing surface scatters in all directions the light which falls upon it, each small element of such a surface is sending out light in a great many directions, in much the same way in which each point on a luminous surface is sending

out light in all directions. Hence we always see the *outline* of a diffusing surface as we do that of an emitting surface, no matter where the eye is placed. On the other hand, when light comes to the eye from a polished reflecting surface, since the form of the beam is wholly undisturbed by the reflection, we see the outline not of the mirror but rather of the source from which the light came to the mirror, whether this source is itself self-luminous or not. All bodies other than self-luminous ones are visible only by the light which they diffuse. Black bodies send no light to the eye, but their outlines can be distinguished by the light which comes from the background. Any object *which can be seen*, therefore, may be regarded as itself sending rays to the eye; that is, it may be treated as a luminous body.

423. Refraction. Let a narrow beam of sunlight be allowed to fall on a thick glass plate with a polished front and whitened back* (Fig. 379). It will be seen to split into a reflected and a transmitted portion. The transmitted portion will be seen to be bent toward the perpendicular *OP* drawn into the glass. Upon emergence into the air it will be bent again, but this time away from the perpendicular *O′P′* drawn into the air. Let the incident beam strike the surface at different angles. It will be seen that *the greater the angle of incidence the greater the bending*. At normal incidence there will be no bending at all. If the upper and lower faces of the glass are parallel, the bending at the two faces will always be the same, so that the emergent beam is parallel to the incident beam.

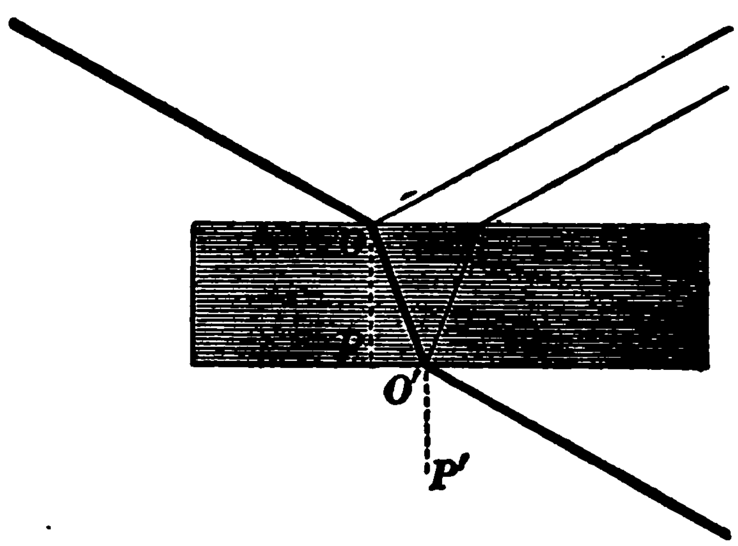


FIG. 379. Path of a ray through a medium bounded by parallel faces

* All of these experiments on reflection and refraction may be done effectively and conveniently by using disks of glass, like those used with the Hartl Optical Disk, through which the beam can be traced.

Similar experiments made with other substances have brought out the general law that *whenever light travels obliquely from one medium into another in which the speed is less it is bent toward the perpendicular, and when it passes from one medium to another in which the speed is greater it is bent away from the perpendicular, drawn into the second medium.*

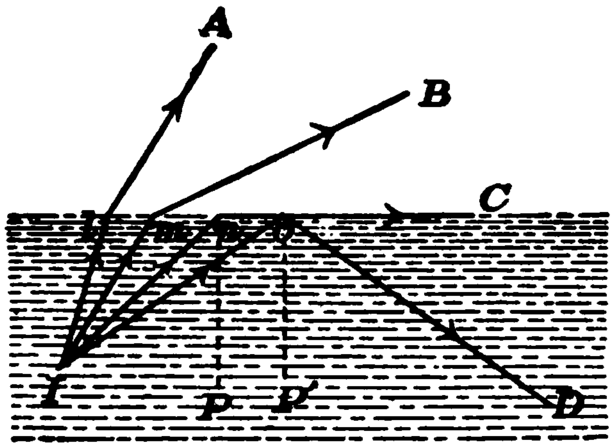


FIG. 380. Rays coming from a source I under water to the boundary between air and water at different angles of incidence

424. Total reflection; critical angle. Since rays emerging from a medium like water into one of less density, like air, are always bent *from* the perpendicular (see IlA, ImB, etc., Fig. 380), it is clear that if the angle of incidence on the under surface of the water is made larger and larger, a point must be reached at which the refracted ray is *parallel to the surface* (see InC, Fig. 380). It is interesting to inquire what will happen to a ray Io which strikes the surface at a still greater angle of incidence IoP'. It will not be unnatural to suppose that since the ray nC just grazed the surface, the ray Io will not be able to emerge at all. The following experiment will show that this is indeed the case.

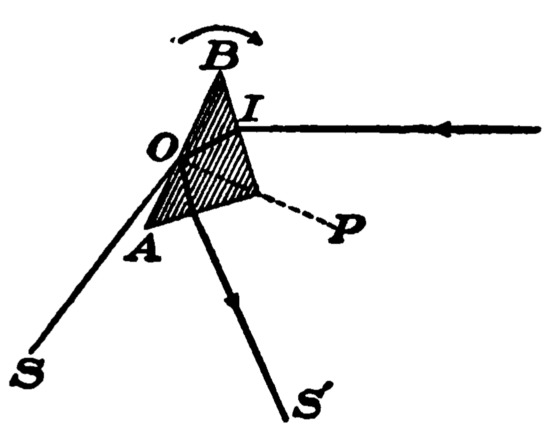


FIG. 381. Transmission and reflection of light at surface AB of a right-angled prism

Let a prism with three polished edges, a polished front, and a whitened back be held in the path of a narrow beam of sunlight, as shown in Fig. 381. If the angle of incidence IOP is small, the beam will divide at O into a reflected and a transmitted portion, the former going to S', the latter to S (neglect the color for the present). Let the prism be rotated slowly in the direction of the arrow. A point will be reached at which the transmitted beam disappears completely, while at the same time the spot at S' shows an appreciable increase in brightness. Since

the transmitted ray OS has totally disappeared, the whole of the light incident at O must be in the reflected beam. The angle of incidence IOP at which this occurs is called the *critical angle.* This angle for crown glass is 42.5°, for water 48.5°, for diamond 23.7°. The critical angle for any substance may be defined as the angle of incidence in that substance for which the angle of refraction into air is 90°.

We learn, then, that *when a ray of light traveling in any medium meets another in which the speed is greater, it is totally reflected if the angle of incidence is greater than a certain angle called the critical angle.*

QUESTIONS AND PROBLEMS

1. In Fig. 382 the portion *acdb* of the shadow is called the umbra, *aec* and *bdf* the penumbra. What kind of source has no penumbra?

2. The sun is much larger than the earth. Draw a diagram showing the shape of the earth's umbra and penumbra.

3. Will it ever be possible for the moon to totally eclipse the sun from the whole of the earth's surface at once?

4. Sirius, the brightest star, is about 52,000,000,000,000 miles away. If it were suddenly annihilated, how long would it shine on for us?

5. Why is a room with white walls much lighter than a similar room with black walls?

FIG. 382. Shadow from a broad source

FIG. 383. Anti-glare "lens" for automobile head-light

6. If the word "white" be painted with white paint (or whiting moistened with alcohol) across the face of a mirror and held in the path of a beam of sunlight in a darkened room, in the middle of the spot on the wall which receives the reflected beam the word "white" will appear in black letters. Explain.

7. Compare the reflection of light from white blotting paper with that from a plane mirror. Which of these objects is more easily seen from a distance? Why?

8. Devise an arrangement of mirrors by means of which you could see over and beyond a high stone wall or trench embankment. This is a very simple form of periscope.

9. Draw diagrams to show in what way a beam of light is bent (a) in passing through a prism; (b) in passing obliquely through a plate-glass window.

10. Explain the effect of the anti-glare "lens" (Fig. 383) upon the light of the automobile.

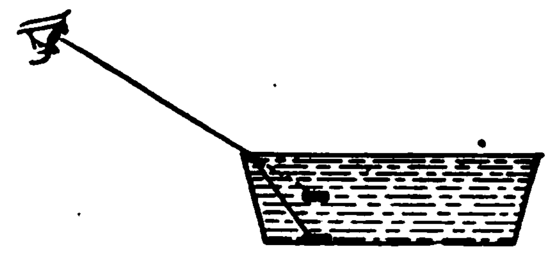


FIG. 384

11. The moon has practically no atmosphere. We know this because when a star appears to pass behind the moon there is no decrease or increase in its apparent velocity while disappearing or coming into view again. If the moon had an atmosphere like the earth, explain how this would affect the apparent velocity of the star at both these times.

12. If a penny is placed in the bottom of a vessel in such a position that the edge just hides it from view (Fig. 384), it will become visible as soon as water is poured into the vessel. Explain.

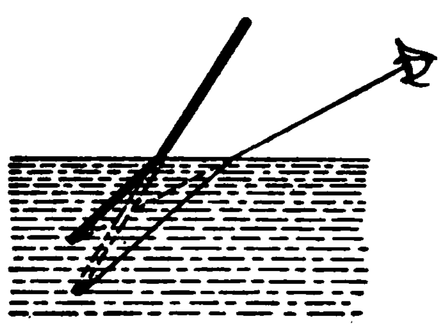


FIG. 385

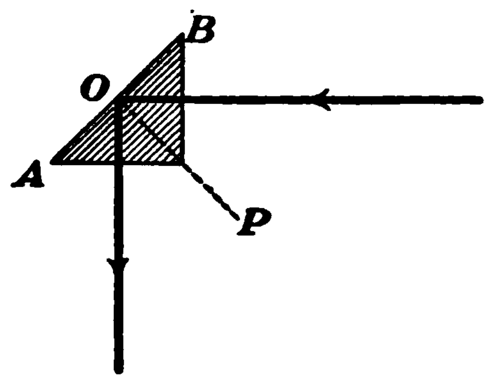


FIG. 386

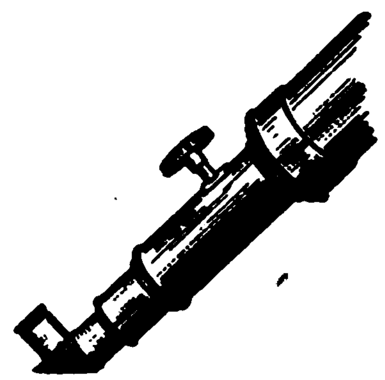


FIG. 387. A diagonal eyepiece

13. A stick held in water appears bent, as shown in Fig. 385. Explain.

14. A glass prism placed in the position shown in Fig. 386 is the most perfect reflector known. Why is it better than an ordinary mirror?

15. Diagonal eyepieces containing a right-angle prism of crown glass (Fig. 387) are used on astronomical telescopes in viewing celestial objects at a high altitude. Explain.

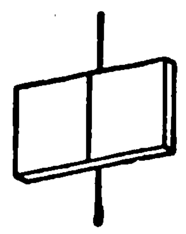


FIG. 388

16. Explain why a straight wire seen obliquely through a piece of glass appears broken, as in Fig. 388.

17. The earth reflects sixteen times as much light to the moon as the moon does to the earth. Trace from the sun to the eye of the observer the light by which he is able to see the dark part of the new moon. Why can we not see the dark part of a third-quarter moon?

The Nature of Light

425. The corpuscular theory of light. All of the properties of light which have so far been discussed are perhaps most easily accounted for on the hypothesis that light consists of streams of very minute particles, or *corpuscles*, projected with the enormous velocity of 300,000 kilometers per second from all luminous bodies. The facts of straight-line propagation and reflection are exactly as we should expect them to be if this were the nature of light. The facts of refraction can also be accounted for, although somewhat less simply, on this hypothesis. As a matter of fact, this theory of the nature of light, known as the *corpuscular theory*, was the one most generally accepted up to about 1800.

426. The wave theory of light. A rival hypothesis, which was first completely formulated by the great Dutch physicist Huygens (1629–1695), regarded light, like sound, as a *form of wave motion*. This hypothesis met at the start with two very serious difficulties. In the first place, light, unlike sound, not only travels with perfect readiness through the best vacuum which can be obtained with an air pump, but it travels without any apparent difficulty through the great interstellar spaces which are probably infinitely better vacua than can be obtained by artificial means. If, therefore, light is a wave motion, it must be a wave motion of some medium which fills all space and yet does not hinder the motion of the stars and planets. Huygens assumed such a medium to exist, and called it the *ether*.

The second difficulty in the way of the wave theory of light was that it apparently failed to account for the fact of straight-line propagation. Sound waves, water waves, and all other forms of waves with which we are most familiar bend readily around corners, while light apparently does not. It was this difficulty chiefly which led many of the most

Christian Huygens (1629–1695)

Great Dutch physicist, mathematician, and astronomer; discovered the rings of Saturn; made important improvements in the telescope; invented the pendulum clock (1656); developed with marvelous insight the wave theory of light; discovered in 1690 the "polarization" of light. (The fact of double refraction was discovered by Erasmus Bartholinus in 1669, but Huygens first noticed the polarization of the doubly refracted beams and offered an explanation of double refraction from the standpoint of the wave theory)

The Great Telescope of the Yerkes Observatory (University of Chicago)

This is the largest *refracting* telescope in the world. The objective is an achromatic lens (see § 475) 40 inches in diameter, which is mounted in a tube 63 feet long. In order to follow the apparent motions of the heavenly bodies due to the rotation of the earth, the entire tubes and counterpoises, weighing 21 tons, are driven by a giant clock. The speed of the clock is controlled by a governor, similar in principle to that of Fig. 184. By means of electric motors the telescope may be pointed in any direction. It is then clamped to the clock, which keeps it pointed toward the same region of the sky as long as may be desired. The entire floor may be raised or lowered to accommodate the observer

famous of the early philosophers, including the great Sir Isaac Newton, to reject the wave theory and to support the projected-particle theory. Within the last hundred years, however, this difficulty has been completely removed, and in addition other properties of light have been discovered for which the wave theory offers the only satisfactory explanation. The most important of these properties will be treated in the next paragraph.

427. Interference of light. Let two pieces of plate glass about half an inch wide and four or five inches long be separated at one end by a thin sheet of paper in the manner shown in Fig. 389, while the other end is clamped or held firmly together, so that a very thin wedge of air exists between the plates. Let a piece of asbestos or blotting paper be soaked in a solution of common salt (sodium chloride) and placed over the tube of a Bunsen burner so as to touch the flame in the manner shown. The flame will be colored a bright yellow by the sodium in the salt. When the eye looks at the reflection of the flame from the glass surfaces, a series of fine black and yellow lines will be seen to cross the plate.

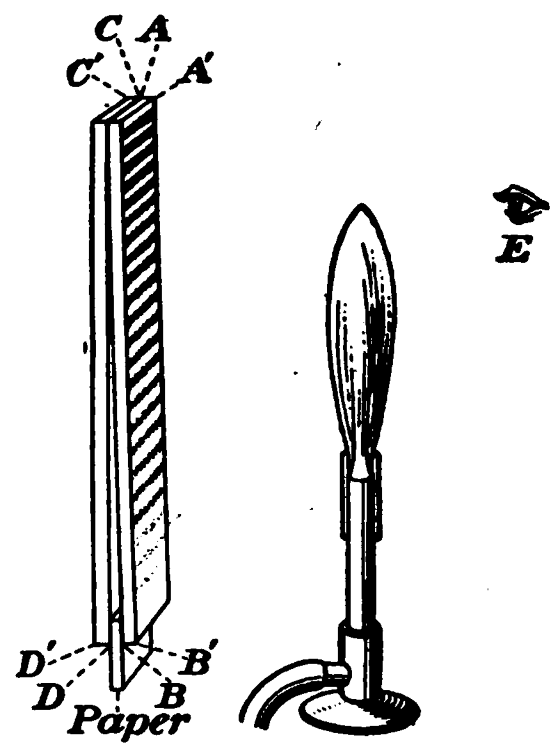


FIG. 389. Interference of light waves

The wave theory offers the following explanation of these effects. Each point of the flame sends out light waves which travel to the glass plate and are in part reflected and in part transmitted at all the surfaces of the glass, that is, at $A'B'$, at AB, at CD, and at $C'D'$ (Fig. 389). We will consider, however, only those reflections which take place at the two faces of the air wedge, namely, at AB and CD. Let Fig. 390 represent a greatly magnified section of these two surfaces. Let the wavy line *as* represent a light wave reflected from the surface AB at the point a, and returning thence to the eye.

Let the dotted wavy line *ir* represent a light wave reflected from the surface *CD* at the point *i*, and returning thence to the eye. Similarly, let all the continuous wavy lines of the figure represent light waves reflected from different points on *AB* to the eye, and let all the dotted wavy lines represent waves reflected from corresponding points on *CD* to the eye. Now, in precisely the same way in which two trains of sound waves from two tuning forks were found, in the experiment illustrating beats (see § 396), to interfere with each other so as to produce silence whenever the two waves corresponded to motions of the air particles in opposite directions, so in this experiment the two sets of light waves from *AB* and *CD* interfere with each other so as to produce darkness wherever these two waves correspond to motions of the light-transmitting medium in opposite directions. The dark bands, then, of our experiment are simply the places at which the two beams reflected from the two surfaces of the air film neutralize or destroy each other, while the light bands correspond to the places at which the two beams reënforce each other and thus produce illumination of double intensity. The position of the second dark band *c* must of course be determined by the fact that the distance from *c* to *k* and back (see Fig. 390) is a wave length more than from *a* to *i* and back, and so on down the wedge. This

Interference
Reënforcement
Interference
Reënforcement
Interference
Reënforcement
Interference
Reënforcement

FIG. 390. Explanation of formation of dark and light bands by interference of light waves

phenomenon of the interference of light is met with in many different forms, and in every case the wave theory furnishes at once a wholly satisfactory explanation of the observed effects, while the corpuscular theory, on the other hand, is unable to account for any of these interference effects without the most fantastic and violent assumptions. Hence *the corpuscular theory is now practically abandoned, and light is universally regarded by physicists as a form of wave motion.*

428. The ether. We have already indicated that if the wave theory is to be accepted, we must conceive, with Huygens, that all space is filled with a medium, called the *ether*, in which the waves can travel. This medium cannot be like any of the ordinary forms of matter; for if any of these forms existed in interplanetary space, the planets and the other heavenly bodies would certainly be retarded in their motions. As a matter of fact, in all the hundreds of years during which astronomers have been making accurate observations of the motions of heavenly bodies no such retardation has ever been observed. The medium which transmits light waves must therefore have a density which is infinitely small even in comparison with that of our lightest gases.

Further, in order to account for the transmission of light through transparent bodies, it is necessary to assume that the ether penetrates not only all interstellar spaces but all intermolecular spaces as well.

429. Wave length of yellow light. Although light, like sound, is a form of wave motion, light waves differ from sound waves in several important respects. In the first place, an analysis of the preceding experiment, which seems to establish so conclusively the correctness of the wave theory, shows that the wave length of light is extremely minute in comparison with that of ordinary sound waves. The wave length of the yellow light used in that experiment is .00006 centimeter (about $\frac{1}{40,000}$ inch).

The *number of vibrations per second* made by the little particles which send out the light waves may be found, as in the case of sound, by

dividing the velocity by the wave length. Since the velocity of light is 30,000,000,000 centimeters per second and the wave length is .00006 centimeter, the number of vibrations per second of the particles which emit yellow light has the enormous value 500,000,000,000,000.

430. Wave theory explanation of refraction. Let one look vertically down upon a glass or tall jar full of water and place his finger on the side of the glass at the point at which the bottom appears to be, as seen through the water (Fig. 391). In every case it will be found that the point touched by the finger will be about one fourth of the depth of the water above the bottom.

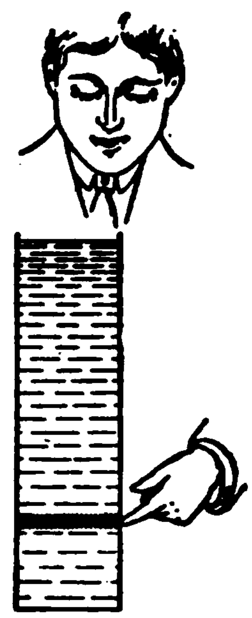


FIG. 391. Apparent elevation of the bottom of a body of water

According to the wave theory this effect is due to the fact that the speed of light is less in water than in air. Thus, consider a wave which originates at any point P (Fig. 392) beneath a surface of water and spreads from that point with equal speed in all directions. At the instant at which the front of this wave first touches the surface at o it will, of course, be of spherical form, having P as its center. Let aob be a section of this sphere. An instant later, if the speed had not changed in passing into air, the wave would have still had P as its center, and its form would have coincided with the dotted line co_1d, so drawn that ac, oo_1, and bd are all equal. But if the velocity in air is *greater* than in water, then at the instant considered the disturbance will have reached some point o_2 instead of o_1, and hence the emerging wave will actually have the form of the heavy line co_2d instead of the dotted line co_1d. Now this wave co_2d is more curved than the old wave aob, and hence it has its center at some point P' above P. In other words, the wave has bulged upward in passing from water into air. Therefore, when a section of this wave enters the eye at E, the wave appears to originate not at P but at P', for the light actually comes to the eye from P' as a center

rather than from P. We conclude, therefore, *that if light travels more slowly in water than in air, all objects beneath the surface of water ought to appear nearer to the eye than they actually are.* This is precisely what we found to be the case in our experiment.

Furthermore, since when the eye is in any position other than E, for example E', the light travels to it over the broken path PdE', the construction shows that light is always bent away from the perpendicular when it passes obliquely into a medium in which the speed is greater. If it had passed into a medium of less speed, the point P would have appeared depressed below its natural position, because the wave, on emerging into the slower medium, instead of bulging upward would be flattened, and therefore would have its center of curvature, or apparent point of origin, below P; hence the oblique rays would have appeared to be bent *toward* the perpendicular, as we found in § 423 to be the case.

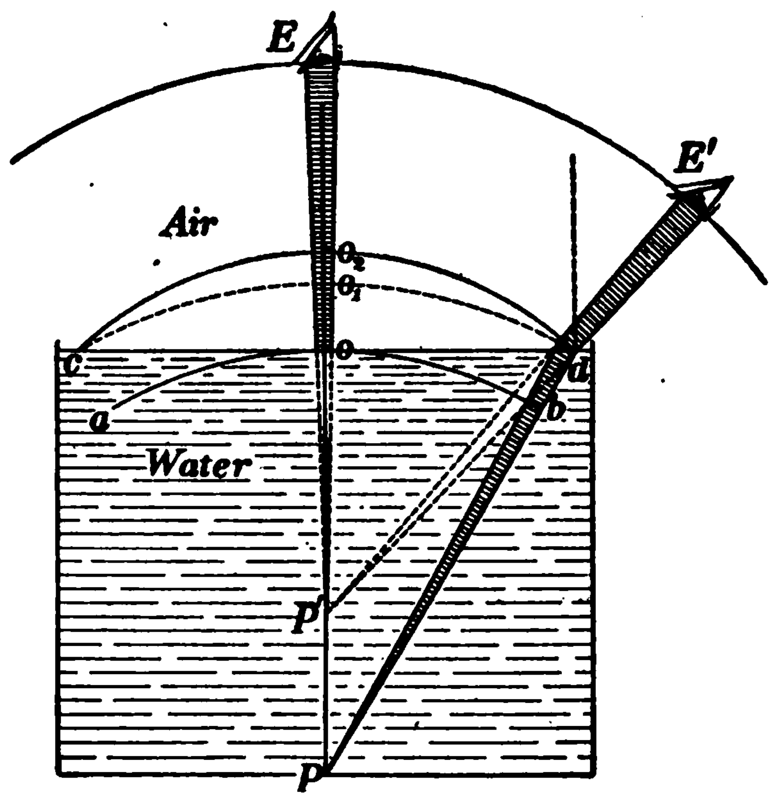


FIG. 392. Representing a wave emerging from water into air

431. The ratio of the speeds of light in air and water. The experiment with the tall jar of water in § 430 not only indicates qualitatively that the speed of light in air is greater than in water, but it furnishes a simple means of determining the ratio of the two speeds. Thus, in Fig. 392 the line oo_2 represents just how far the wave travels in air while it is traveling the distance $ac (= oo_1)$ in water. Hence $\frac{oo_2}{oo_1}$ is the ratio of the speeds of light in air and in water.

Now the curvatures of the arcs co_2d and co_1d are measured by the reciprocals of their respective radii*; that is,

$$\frac{\text{Curvature of } co_2d}{\text{Curvature of } co_1d} = \left(\frac{\frac{1}{dP'}}{\frac{1}{dP}}\right) = \frac{dP}{dP'}. \tag{1}$$

Now when the arcs are small, a condition which in general is realized in experimental work, their curvatures are proportional to the extent to which they bulge out from the straight line cod†; that is,

$$\frac{\text{Curvature of } co_2d}{\text{Curvature of } co_1d} = \left(\frac{oo_2}{oo_1}\right) = \frac{\text{speed in air}}{\text{speed in water}}. \tag{2}$$

From (1) and (2) we get

$$\frac{\text{Speed in air}}{\text{Speed in water}} = \frac{dP}{dP'}. \tag{3}$$

* Construct an angle of 45° (Fig. 393, (1)). Its arc contains 45° and the angle formed by the tangents t, t' is 45°. Now with a radius three times as great (Fig. 393, (2)) draw an arc whose length is equal to that of the arc in Fig. 393 (1). Since the radius is three times as great, this arc contains 15°, and the angle formed by the tangents is 15°. From this we see that the arc whose radius is *three times as great* curves, or changes its direction, *one third as fast*; that is, the change in curvature of an arc of given length varies inversely with the radius. In general then, *the curvature of an arc is measured by the reciprocal of its radius.*

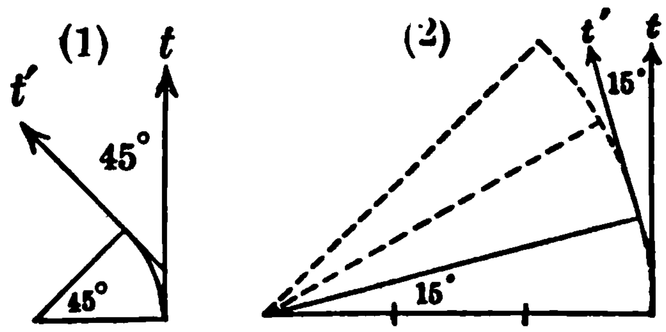


FIG. 393

† oc (Fig. 394) is a mean proportional between the two segments of the diameter; hence $ao \times od = \overline{oc}^2$. For very small arcs od is practically equal to the diameter $2r$. Hence $ao = \frac{\overline{oc}^2}{2r}$, or $ao = \frac{\overline{oc}^2}{2} \times \frac{1}{r}$. Therefore ao is proportional to $\frac{1}{r}$. *That is, the distances to which two small arcs having a common chord bulge out from the chord are proportional to the respective curvatures of the arcs.*

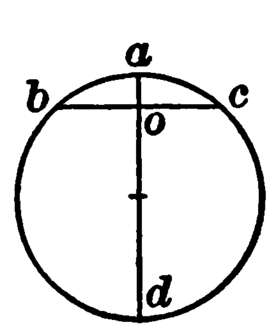


FIG. 394

But in looking vertically downward, as in the experiment with the jar of water, $\frac{dP}{dP'}$ becomes $\frac{oP}{oP'}$; hence,

$$\frac{\text{Speed in air}}{\text{Speed in water}} = \frac{oP}{oP'} = \frac{\text{real depth}}{\text{apparent depth}}.$$

But in our experiment we found that the bottom was apparently raised one fourth of the depth; that is, that $\frac{oP}{oP'} = \frac{4}{3}$. We conclude, therefore, that light travels three fourths as fast in water as in air.

The fact that the value of this ratio, as determined by this indirect method, is exactly the same as that found by Foucault and Michelson (see opposite p. 358) by direct measurement (§ 419) furnishes one of the strongest proofs of the correctness of the wave theory.

432. Index of refraction. The *ratio of the speed of light in air to its speed in any other medium is called the index of refraction of that medium.* It is evident that the method employed in the last paragraph for determining the index of refraction of water can be easily applied to any transparent medium whether liquid or solid.* The refractive indices of some of the commoner substances are as follows:

Water	1.33	Crown glass	1.53
Alcohol	1.36	Flint glass	1.67
Turpentine	1.47	Diamond	2.47

433. Light waves are transverse. Thus far we have discovered but two differences between light waves and sound waves; namely, the former are disturbances in the ether and are of very short wave length, while the latter are disturbances in

* To show the extreme beauty, simplicity, and accuracy of this method of getting index of refraction it is suggested that the teacher use the following method in his laboratory work.

A very sharp pencil must be used for this exercise. Make a dot P on a sheet of paper. Put the glass plate (Fig. 395, (1)) on the sheet so that the

ordinary matter and are of relatively great wave length. There exists, however, a further radical difference which follows from a capital discovery made by Huygens (see opposite p. 364) in the year 1690. It is this: While sound waves consist, as we have already seen, of *longitudinal* vibrations of the particles of the transmitting medium, that is, vibrations back and forth in the line of propagation of the wave, light waves are like the water waves of Fig. 346, p. 324, in that they consist of *transverse* vibrations, that is, vibrations of the medium at right angles to the direction of the line of propagation.

In order to appreciate the difference between the behavior of waves of these two types under certain conditions, conceive

edge of the label pasted around the edge of the glass coincides with the dot (or in case a prism (Fig. 395, (2)) is used, let the apex P coincide with the dot). Draw the base line ef and the other sides of the glass, holding it firmly down meanwhile. Be sure that at no time during the exercise does the glass slip the slightest from its first position. Lay a ruler upon the paper in a slantwise position cd (not touching the glass), and, with one eye closed, make its edge point exactly at the apparent position of P as seen through the glass. If you are now sure that your ruler did not push the glass out of position, draw a line cd with the sharp pencil. Similarly, draw another line ab about as far to the right of the center as cd is to the left. Remove your glass and complete the drawing as indicated in the diagram.

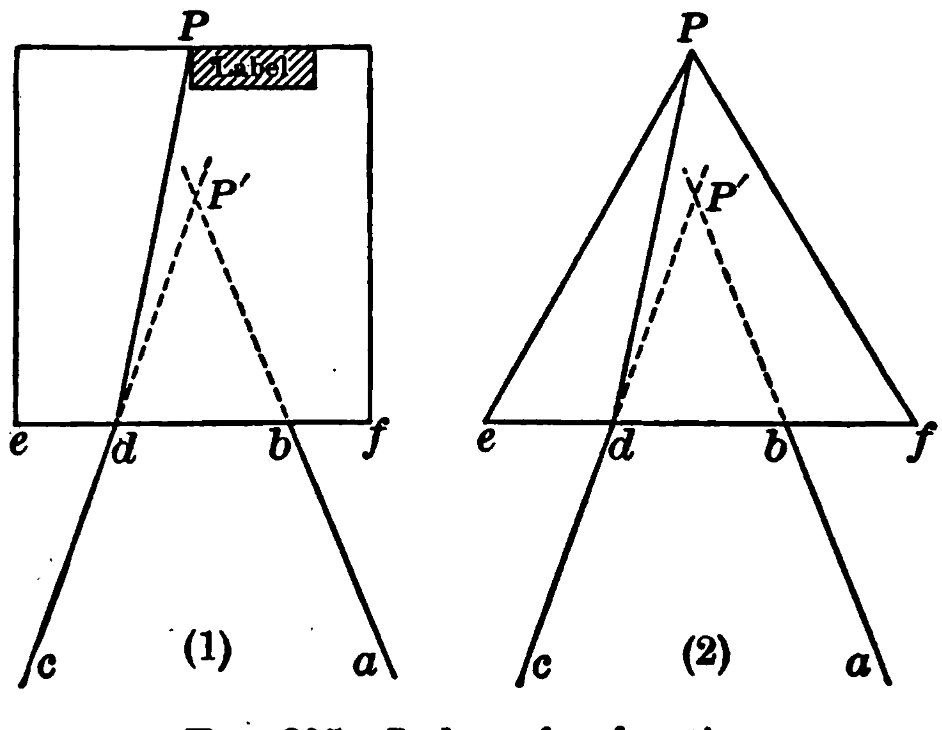


FIG. 395. Index of refraction

P' is the apparent position of P. As you have already learned from your text, the ratio of the velocities of light in air and glass is found by dividing dP by dP'. Measure these distances very carefully to 0.1 mm., and calculate the index of refraction to two decimal places. Make two or three more trials and compare results.

of transverse waves in a rope being made to pass through two gratings in succession, as in Fig. 396. So long as the slits in both gratings are parallel to the plane of vibration of the hand, as in Fig. 396, (1), the waves can pass through them with perfect ease; but if the slits in the first grating P are parallel to the direction of vibration, while those of the second grating Q are turned at right angles to this direction, as in Fig. 396, (2), it is evident that the waves will pass readily through P, but will be stopped completely by Q, as shown in the figure. In other words, these gratings P and Q will let through only such vibrations as are parallel to the direction of their slits.

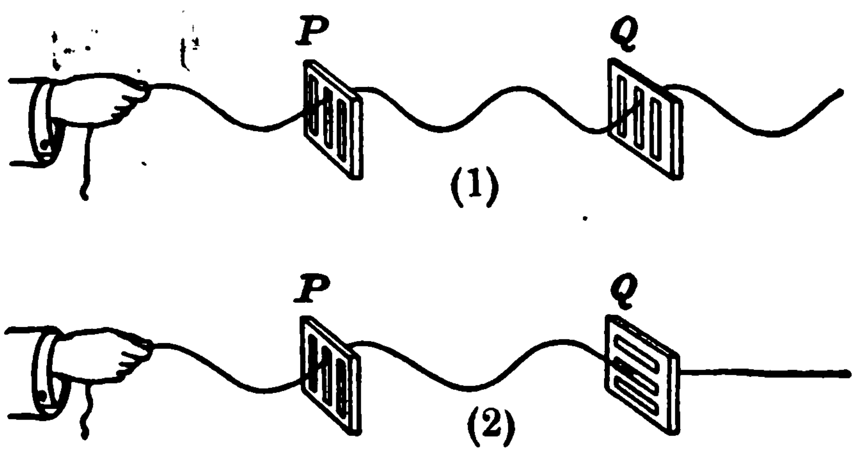


FIG. 396. Transverse waves passing through slits

If, on the other hand, a longitudinal instead of a transverse wave — such, for example, as a sound wave — had approached such a grating, it would have been as much transmitted in one position of the grating as in another, since a *to-and-fro* motion of the particles can evidently pass through the slits with exactly the same ease, no matter how they are turned.

Now two crystals of tourmaline are found to behave with respect to light waves just as the two gratings behave with respect to the waves on the rope.

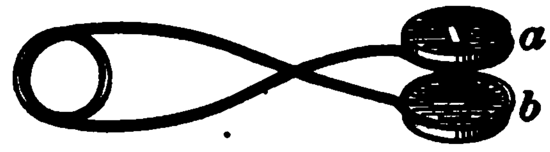


FIG. 397. Tourmaline tongs

Let one such crystal a (Fig. 397) be held in front of a small hole in a screen through which a beam of sunlight is passing to a neighboring wall; or, if the sun is not shining, simply let the crystal be held between the eye and a source of light. The light will be readily transmitted, although somewhat diminished in intensity. Then let a second crystal b be held in line with the first. The light will still be transmitted, *provided the axes of*

the crystals are parallel, as shown in Fig. 398. When, however, one of the crystals is rotated in its ring through 90° (Fig. 399), the light *is cut off.* This shows that a crystal of tourmaline is capable of transmitting only light which is vibrating in one particular plane.

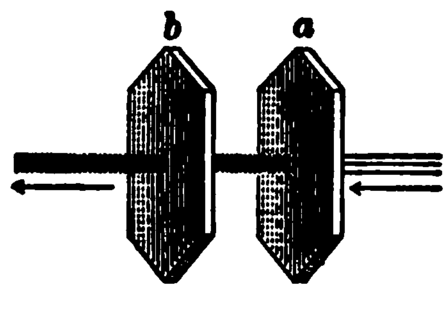


FIG. 398. Light passing through tourmaline crystals

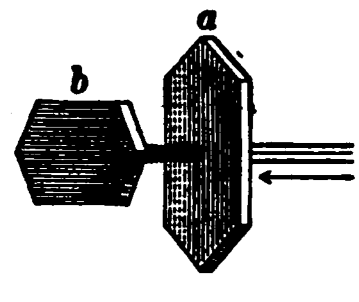


FIG. 399. Light cut off by crossed tourmaline crystals

From this experiment, therefore, we are forced to conclude that *light waves are transverse rather than longitudinal vibrations.* The experiment illustrates what is technically known as the *polarization of light,* and the beam which, after passage through *a*, is unable to pass through *b* if the axes of *a* and *b* are crossed, is known as a *polarized beam.* It is, then, the phenomenon of the *polarization of light* upon which we base the conclusion that light waves are transverse.

434. Intensity of illumination. Let four candles be set as close together as possible in such a position *B* as to cast upon a white screen *C*, placed in a well-darkened room, a shadow of an opaque object *O* (Fig. 400). Let one single candle be placed in a position *A* such that it will cast another shadow of *O* upon the screen. Since light from *A* falls on the shadow cast by *B*, and light from *B* falls on the shadow cast by *A*, it is clear that the two shadows will appear equally dark only when light of equal intensity falls on each; that is, when *A* and *B* produce equal illumination upon the screen. Let the positions of *A* and *B* be shifted until this condition is fulfilled. Then let the distances from *B* to *C* and from *A* to *C* be measured. If all five candles are burning with flames of the same size, the first distance will be found to be just twice as great as the second. Hence the illumination produced upon the screen by each one of the candles at *B* is but one fourth as great as that produced on the screen by one candle at *A*, one half as far away.

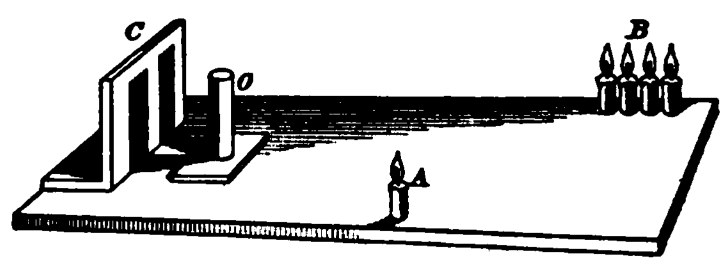


FIG. 400. Rumford's photometer

The above is the direct experimental proof that *the intensity of illumination varies inversely as the square of the distance from the source.*

The theoretical proof of the law is furnished at once by Fig. 401, for since all the light which falls from the candle L on A is spread over four times as large an area when it reaches B, twice as far away, and over nine times as large an area

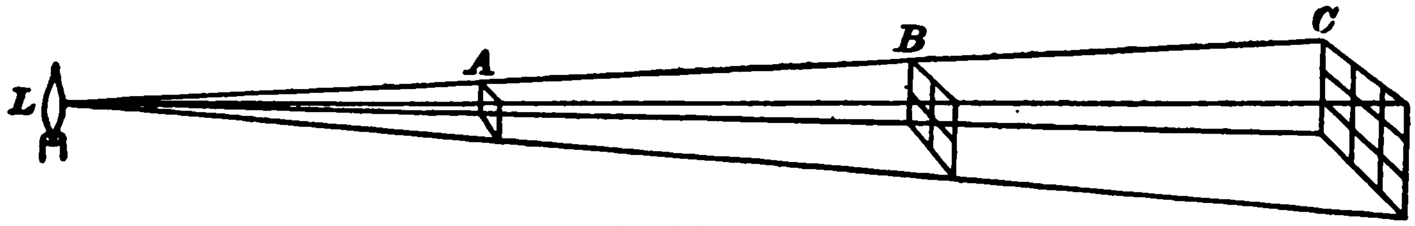


FIG. 401. Proof of law of inverse squares

when it reaches C, three times as far away, obviously the *intensities* at B and at C can be but one fourth and one ninth as great as at A.

The above method of comparing experimentally the intensities of two lights was first used by Count Rumford. The arrangement is therefore called the *Rumford photometer* (light measurer).

435. Candle power. The last experiment furnishes a method of comparing the *light-emitting powers* of various sources of light. For example, suppose that the four candles at B are replaced by a gas flame, and that for the condition of equal illumination upon the screen the two distances BC and AC are the same as above, namely, 2 to 1. We should then know that the gas flame, which is able to produce the same illumination at a distance of two feet as a candle at a distance of one foot, has a light-emitting power equal to four candles. In general, then, *the candle powers of any two sources which produce equal illumination on a given screen are directly proportional to the squares of the distances of the sources from the screen.*

It is customary to express the intensities of all sources of light in terms of candle power, one candle power being defined as the amount of light emitted by a sperm candle $\frac{7}{8}$ inch in

diameter and burning 120 grains (7.776 grams) per hour. The candle power of an ordinary gas flame burning 5 cubic feet per hour is from 16 to 25, depending on the quality of the gas.

A standard candle at a distance of 1 foot gives an intensity of illumination called a *foot-candle.* A 100-candle-power lamp, for example, at a distance of 1 foot gives an intensity of illumination of 100 foot-candles; at 2 feet, of 25 foot-candles; at 5 feet, of 4 foot-candles; and at 10 feet, of 1 foot-candle.

436. Bunsen's photometer. Let a drop of oil or melted paraffin be placed in the middle of a sheet of unglazed white paper to render it translucent. Let the paper be held near a window and the side *away from* the window observed. The oiled spot will appear *lighter* than the remainder of the paper. Then let the paper be held so that the side nearest the window may be seen. The oiled spot will appear *darker* than the rest of the paper. We learn, therefore, that *when the paper is viewed from the side of greater illumination, the oiled spot appears dark;* but *when it is viewed from the side of lesser illumination, the spot appears light.* If, then, the two sides of the paper are equally illuminated, the spot ought to be of the same brightness when viewed from either side. Let the room be darkened and the oiled paper placed between two gas flames, two electric lights, or any two equal sources of light. It will be observed that when the paper is held closer to one than the other, the spot will appear dark when viewed from the side next the closer light; but if it is then moved until it is nearer the other source, the spot will change from dark to light when viewed always from the same side. It is always possible to find some position for the oiled paper at which the spot either disappears altogether or at least appears the same when viewed from either side. This is the position at which the illuminations from the two sources are equal. Hence, to find the candle power of any unknown source it is only necessary to set up a candle on one side and the unknown source on the other, as in Fig. 402, and to move the spot A to the position of equal illumination. The candle power of the unknown source at C will then be the square of the distance from C to A, divided by the square of the distance from B to A.

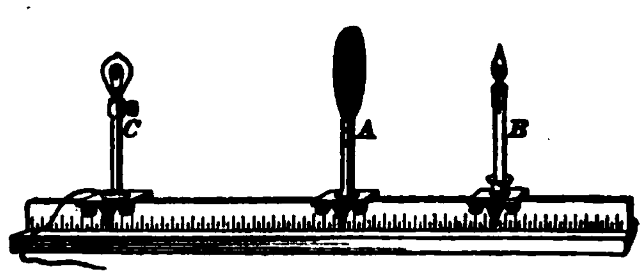


FIG. 402. Bunsen's photometer

This arrangement is known as the *Bunsen photometer.*

QUESTIONS AND PROBLEMS

1. Distinguish between candle power, intensity of light, and intensity of illumination.

2. How many candles will be required to produce the same intensity of illumination at 2 m. that is produced by 1 candle at 30 cm.?

3. A 500-candle-power lamp is placed 50 m. from a darkly shaded place along the street. At what distance would a 100-candle-power lamp have to be to produce the same intensity of illumination?

4. If a 2-candle-power light at a distance of 1 ft. gives enough illumination for reading, how far away must a 32-candle-power lamp be placed to make the same illumination? How strong a lamp should be used at a distance of 8 ft. from the book?

5. A Bunsen photometer placed between an arc light and an incandescent light of 32 candle power is equally illuminated on both sides when it is 10 ft. from the incandescent light and 36 ft. from the arc light. What is the candle power of the arc?

6. A 5-candle-power and a 30-candle-power source of light are 2 m. apart. Where must the oiled disk of a Bunsen photometer be placed in order to be equally illuminated on the two sides by them?

7. If the sun were at the distance of the moon from the earth, instead of at its present distance, how much stronger would sunlight be than at present? The moon is 240,000 mi. and the sun 93,000,000 mi. from the earth.

8. If a gas flame is 300 cm. from the screen of a Rumford photometer, and a standard candle 50 cm. away gives a shadow of equal intensity, what is the candle power of the gas flame?

9. Will a beam of light going from water into flint glass be bent toward or away from the perpendicular drawn into the glass?

10. When light passes obliquely from air into carbon bisulphide it is bent more than when it passes from air into water at the same angle. Is the speed of light in carbon bisulphide greater or less than in water?

11. If light travels with a velocity of 186,000 miles per sec. in air, what is its velocity in water, in crown glass, and in diamond? (See table of indices of refraction, p. 371.)

CHAPTER XIX

IMAGE FORMATION

IMAGES FORMED BY LENSES

437. Focal length of a convex lens. Let a convex lens be held in the path of a beam of sunlight which enters a darkened room, where it is made plainly visible by means of chalk dust or smoke. The beam will be found to converge to a focus F, as shown in Fig. 403.

The explanation is as follows: The waves from the sun or any distant object are without any appreciable curvature when they strike the lens; that is, they are so-called *plane waves* (see Fig. 403). Since the speed of light is less in glass than in air, the central portion of these waves is retarded more than the outer portions in passing through the lens. Hence, on emerging from the lens the waves are concave instead of plane, and close in to a center or *focus* at F.

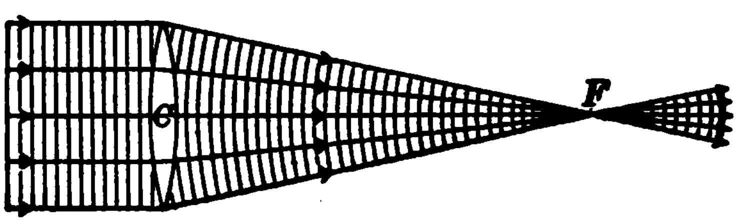


FIG. 403. Principal focus F and focal length CF of a convex lens

A second way of looking at the phenomenon is to think of the "rays" which strike the lens as being bent by it, in accordance with the laws given in § 423, so that they all pass through the point F.

The line through the point C (the *optical center*) of the lens, perpendicular to its faces, is called the *principal axis*.

The point F at which rays parallel to the principal axis (incident plane waves) are brought to a focus is called the *principal focus*.

The distance CF from the center of the lens to the principal focus is called the *focal length* (f) of the lens.

The plane $F'FF''$ (Fig. 404) in which plane waves (parallel rays) coming to the lens from slightly different directions, as from the top and bottom of a distant house, all have their foci F', F'', etc. is called the *focal plane* of the lens.

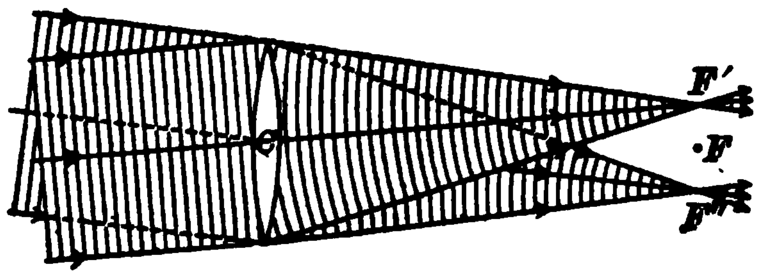


FIG. 404. Focal plane of a convex lens

Since the curvature of any arc is defined as the reciprocal of its radius (see footnote, p. 370), *the curvature which a lens impresses on an incident plane wave is equal to* $\frac{1}{f}$. Moreover, no matter what the curvature of an incident wave may be, *the lens will always change the curvature by the same amount,* $\frac{1}{f}$.

Let the focal length of a convex lens be accurately determined by measuring the distance from the middle of the lens to the image of a distant house.

438. Conjugate foci. If a point source of light is placed at F (Fig. 403), it is obvious that the light which goes through the lens must exactly retrace its former path; that is, its

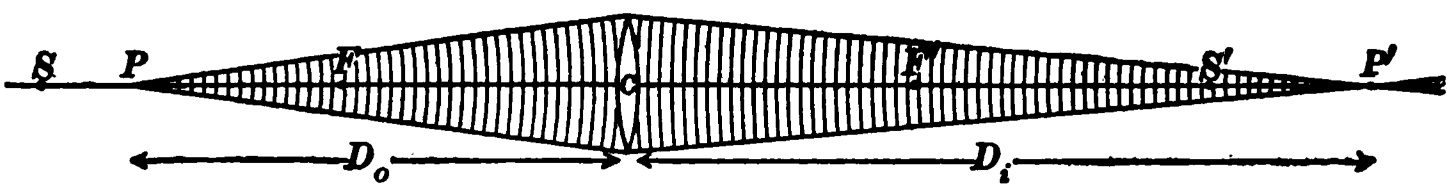


FIG. 405. Conjugate foci

waves will be rendered plane or its rays parallel by the lens. But if the point source is at a distance D_o greater than f (Fig. 405), then the waves upon striking the lens have a curvature $\frac{1}{D_o}$ (since the curvature of an arc is defined as the reciprocal of its radius), which is less than their former curvature, $\frac{1}{f}$. Since the lens was able to subtract all the

curvature from waves coming from F and render them plane, by subtracting the same curvature from the flatter waves from P it must render them concave; that is, the rays after passing through the lens are converging and intersect at P'. If the source is placed at P', obviously the rays will meet at P. Points such as P and P', so related that one is the image of the other, are called *conjugate foci.*

439. Formula for conjugate foci; secondary foci. Since in Fig. 405 the curvature of the wave when it emerges from the lens is opposite in direction to its curvature when it reaches the lens, the *sum* of these curvatures, $\frac{1}{D_o}+\frac{1}{D_i}$, represents the power of the lens to change the curvature of the incident wave, which by § 437 is $\frac{1}{f}$. Hence

$$\frac{1}{D_o}+\frac{1}{D_i}=\frac{1}{f}; \tag{1}$$

that is, *the sum of the reciprocals of the distances of the conjugate foci from the lens is equal to the reciprocal of the focal length.* If $D_o = D_i$, then the equation shows that both D_o and D_i are equal to $2f$.

The two conjugate foci S and S' which are at equal distances from the lens are called the *secondary foci*, and their distance from the lens is twice the focal distance.

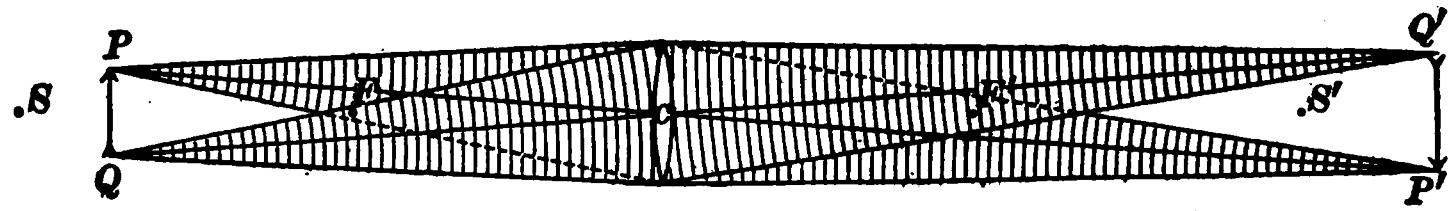


FIG. 406. Formation of a real image by a lens

440. Images of objects. Let a candle or electric-light bulb be placed between the principal focus F and the secondary focus S at PQ (Fig. 406), and let a screen be placed at $P'Q'$. An enlarged inverted image will be seen upon the screen.

This image is formed as follows: All the light which strikes the lens from the point P is brought together at a point P'. *The location of this image P' must be on a straight line drawn from P through C; for any ray passing through C will remain parallel to its original direction, since the portions of the lens through which it enters and leaves may be regarded as small parallel planes* (see § 423). *The image $P'Q'$ is therefore always formed between the lines drawn from P and Q through C.* If the focal length f and the distance of the object D_o are known, the distance of the image D_i may be obtained easily from formula (1).

The position of the image may also be found graphically as follows: Of the cone of rays passing from P to the lens, that

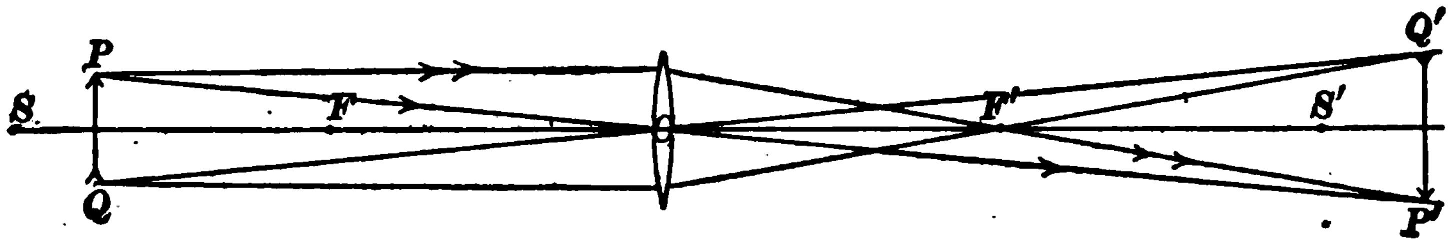


FIG. 407. Ray method of constructing an image

ray which is parallel to the principal axis must, by § 437, pass through the principal focus F. The intersection of this line with the straight line through C locates the image P' (see Fig. 407). Q', the image of Q, is located similarly.

441. Size of image. Since the image and object are always between the intersecting straight lines PP' and QQ', the similar triangles PCQ and $P'CQ'$ show that

$$\frac{PQ}{P'Q'} = \frac{D_o}{D_i}; \tag{2}$$

that is, $\dfrac{\text{Length of object}}{\text{Length of image}} = \dfrac{\text{distance of object from lens}}{\text{distance of image from lens}}.$

It may be seen from Fig. 407, as well as from formulas (1) and (2), that

1. When the object is at S the image is at S', and image and object are of the same size.

2. As the object moves out from S to a great distance the image moves from S' up to F', becoming smaller and smaller.

3. As the object moves from S up to F the image moves out to a very great distance to the right, becoming larger and larger.

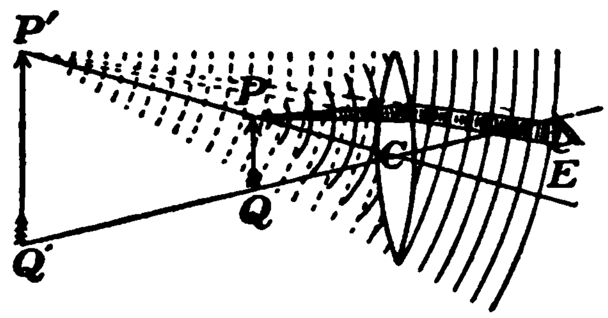


FIG. 408. Virtual image formed by a convex lens

4. When the object is at F the emerging waves are plane (the emerging rays are parallel), and no real image is formed.

442. Virtual image. We have seen that when the object is at F the waves after passing through the lens are plane. If, then, the object is nearer to the lens than F, the emerging waves, although reduced in curvature, will still be convex, and, if received by an eye at E, will appear to come from a point P' (Fig. 408). Since, however, there is actually no source of light at P', this sort of image is called a *virtual image.* Such an image cannot be projected upon a screen as a real image can, but must be observed by an eye.

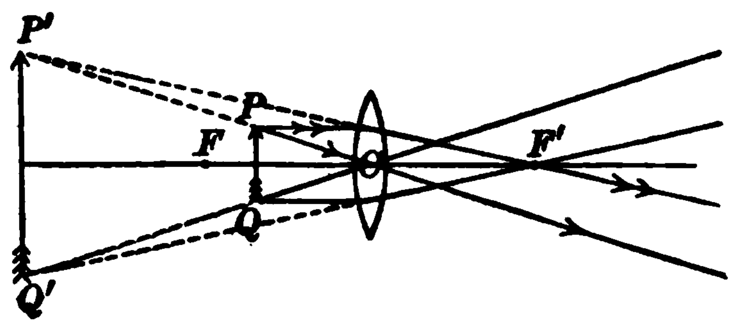


FIG. 409. Ray method of locating a virtual image in a convex lens

The graphical location of a virtual image may be accomplished precisely as in the case of a real image (§ 440). It will be seen that in this case (Figs. 408 and 409) *the image is enlarged and erect.*

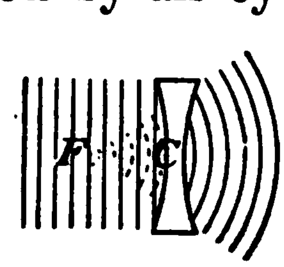


FIG. 410. Virtual focus of a concave lens

443. Image in concave lens. When a plane wave strikes a concave lens, it must emerge as a divergent wave, since the middle of the wave is retarded by the glass less than the edges (Fig. 410). The point F from which plane waves appear to come after passing through such a lens is the principal focus of the lens. For the same

reason as in the case of the convex lens the centers of the transmitted waves from P and Q (Fig. 411), that is, the images P' and Q', must lie upon the lines PC and QC; and since the

FIG. 411. Image in a concave lens

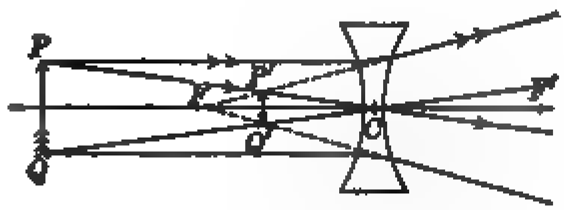


FIG. 412. Ray method of locating an image in a concave lens

curvature is increased by the lens, they must lie closer to the lens than P and Q. Fig. 411 shows the way in which such a lens forms an image. This image is always *virtual, erect, and diminished.* The graphical method of locating the image is shown in Fig. 412.

IMAGES IN MIRRORS

444. Image of a point in a plane or a curved mirror. We are all familiar with the fact that to an eye at E (Fig. 413), looking into a plane mirror mn, a pencil point at P appears to be at some point P' behind the mirror. We are able in the laboratory to find experimentally the exact location of this image P' with respect to P and the mirror, but we may also obtain this location from theory as follows: Consider a light wave which originates in the point P (Fig. 413) and spreads in all directions. Let aob be a section of the wave at the instant at which it reaches the reflecting surface mn. An instant later, if there were no reflecting surface, the wave would have reached the position of the dotted line co_1d.

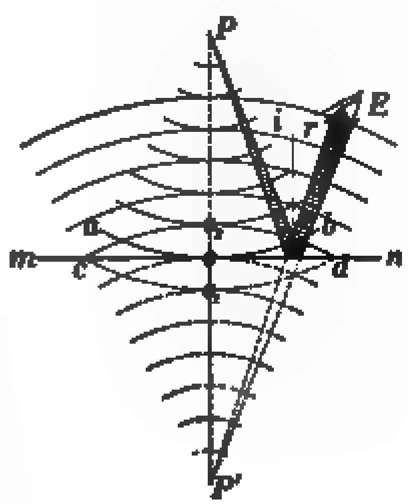


FIG. 413. Wave reflected from a plane surface

Since, however, reflection took place at *mn*, and since the reflected wave is propagated backward with exactly the same velocity with which the original wave would have been propagated forward, at the proper instant the reflected wave must have reached the position of the line co_2d, so drawn that oo_1 is equal to oo_2. Now the wave co_2d has its center at some point P', and it will be seen that P' must lie just as far below *mn* as P lies above it, for co_1d and co_2d are arcs of equal circles

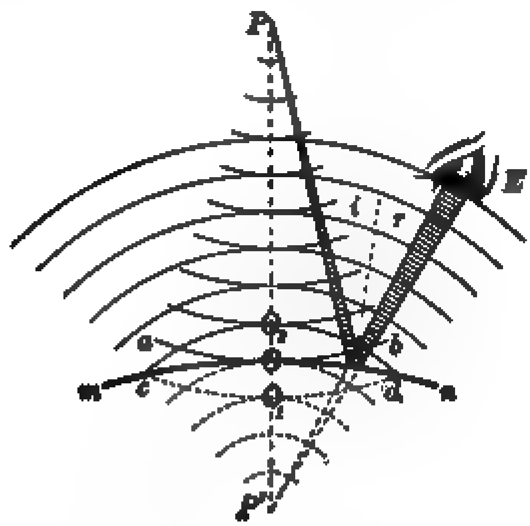


Fig. 414. Wave reflected from a convex surface

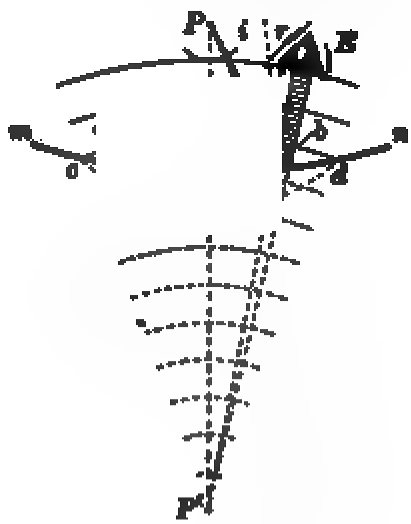


Fig. 415. Wave reflected from a concave surface

having the common chord *cd*. For the same reason, also, P' must lie on the perpendicular drawn from P through *mn*. When, then, a section of this reflected wave co_2d enters the eye at E, the wave appears to have originated at P' and not at P, for the light actually comes to the eye from P' as a center rather than from P. Hence P' is the image of P. We learn, therefore, that *the image of a point in a plane mirror lies on the perpendicular drawn from the point to the mirror and is as far back of the mirror as the point is in front of it.*

Precisely the same construction applied to curved mirrors shows at once (Fig. 414 and Fig. 415) that *the image of a point in any mirror, plane or curved, must lie on the perpendicular drawn from the point to the mirror; but if the mirror*

is convex, the image is nearer to it than is the point, while if it is concave, the image, if formed behind the mirror at all (that is, if it is virtual), is farther from the mirror than is the point.

445. Construction of image of object in a plane mirror. The image of an object in a plane mirror (Fig. 416) may be located by applying the law proved above for each of its points, that is, *by drawing from each point a perpendicular to the reflecting surface and extending it an equal distance on the other side.*

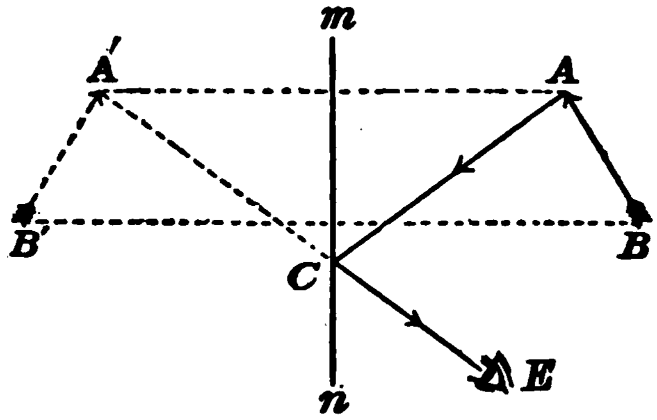


FIG. 416. Construction of image of object in a plane mirror

To find the path of the rays which come to an eye placed at E from any point of the object, such as A, we have only to draw a line from the image A' of this point to the eye and connect the point of intersection of this line with the mirror, namely C, with the original point A. ACE is then the path of the ray.

Let a candle (Fig. 417) be placed exactly as far in front of a pane of window glass as a bottle full of water is behind it, both objects being on the same perpendicular drawn through the glass. The candle will appear to be burning inside the water. This explains a large class of familiar optical illusions, such as the "figure suspended in mid-air," the "bust of a person without a trunk," the "stage ghost," etc. In the last case the illusion is produced by causing the audience to look at the actors obliquely through a sheet of very clear plate glass, the edges of which are concealed by draperies. Images of strongly illuminated figures at one side then appear to the audience to be in the midst of the actors.

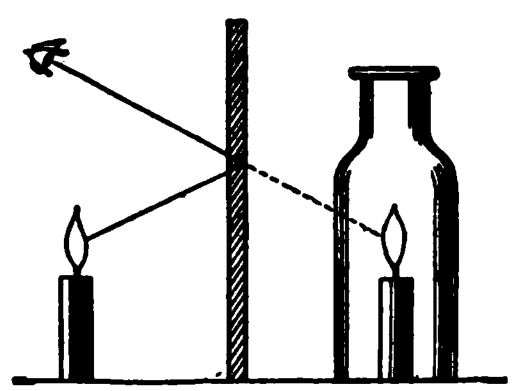


FIG. 417. Position of image in a plane mirror

446. Focal length of a curved mirror half its radius of curvature. The effect of a convex mirror on plane waves incident upon it is shown in Fig. 418. The wave which would at a

given instant have been at co_1d is at co_2d, where $oo_1 = oo_2$. The center F from which the waves appear to come to the eye E is the *focus* of the mirror.

Now so long as the arc cod is small its curvature may, without appreciable error, be measured by o_1o (see footnote, p. 370); that is, by the departure of the curved line cod from the straight line co_1d. Since o_1o was made equal to oo_2, we have $o_1o_2 = 2\,o_1o$; that is, the curvature $\frac{1}{f}$ of the reflected wave is equal to twice the curvature of the mirror, or $\frac{1}{f} = 2 \times \frac{1}{R}$; hence $f = \frac{R}{2}$. In other words, *the focal length of a mirror is equal to one half its radius.*

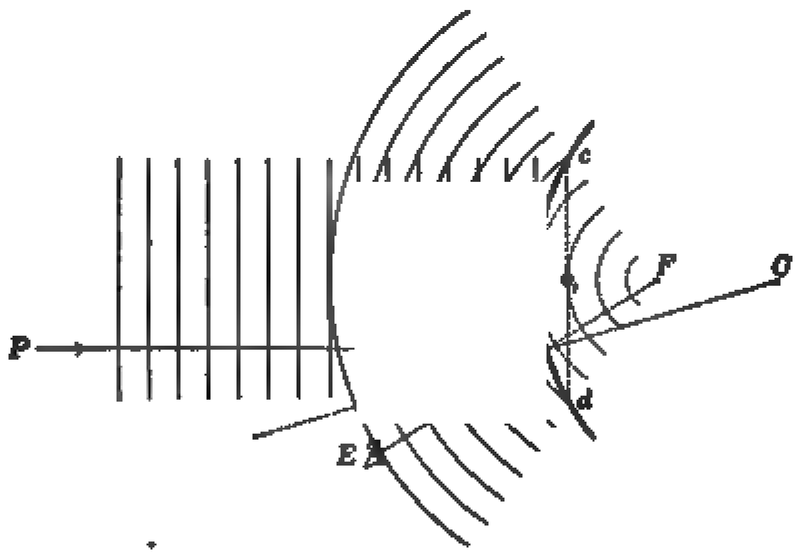


FIG. 418. Reflection of a plane wave from a convex mirror

447. Image of an object in a convex mirror. We are all familiar with the fact that a convex mirror always forms behind the mirror a virtual, erect, and diminished image. The reason for this is shown clearly in Fig. 419. The image of the point P lies, as in plane mirrors (see § 444), always on the perpendicular to the mirror, but now necessarily nearer to the mirror than the focus F, since, as the point P is moved from a position very close to the mirror, where

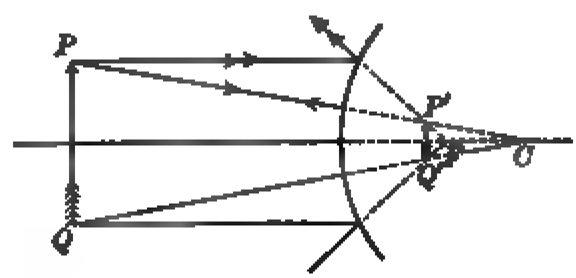
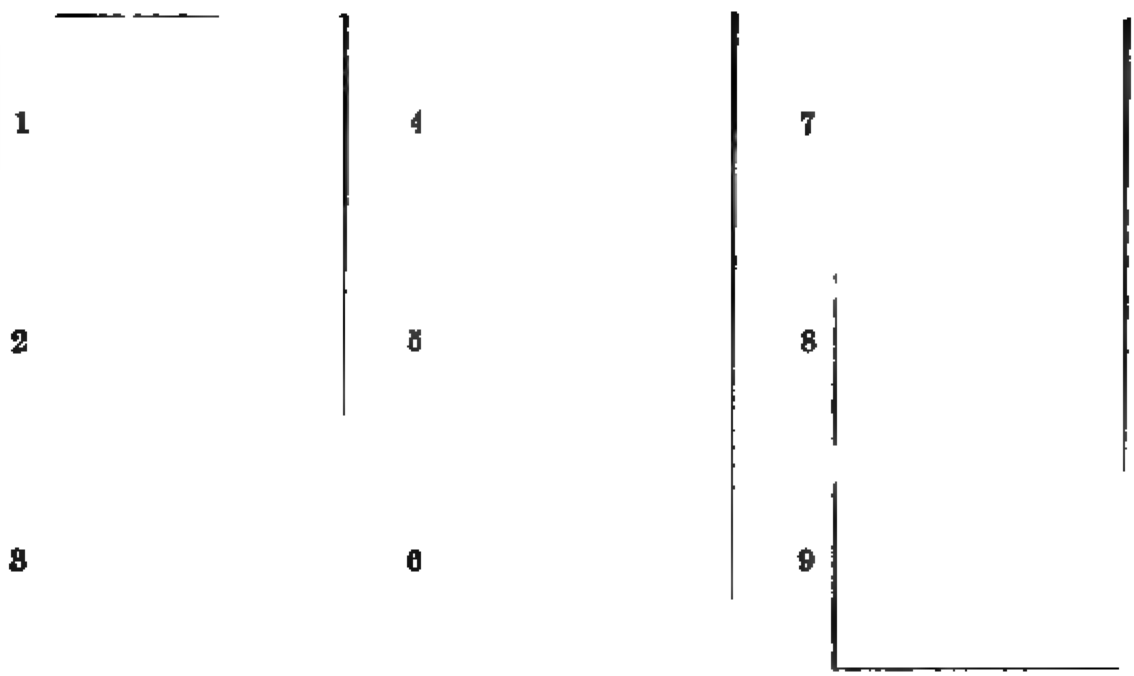


FIG. 419



SECTION OF A "MOVIE" FILM SHOWING SECRETARY OF WAR BAKER TURNING HIS HEAD TO SPEAK TO GENERAL PERSHING

The moving-picture camera makes a series of snapshots upon a film, usually at the rate of 16 per second. The film is drawn past the lens with a jerky movement, being held at rest during the instant of exposure and moved forward while the shutter is closed. The pictures are $\frac{3}{4}$-inch high and 1 inch wide. Since 1 foot of film per second is drawn past the lens, a reel of film 1000 feet long (the usual length) contains 16,000 pictures. From the reel of negatives a reel of positives is printed for use in the projection apparatus. The optical illusion of "moving" pictures is made possible by a peculiarity of the eye called *persistence of vision.* To illustrate this let a firebrand be rapidly whirled in a circle. The spot of light appears drawn into a luminous arc. This phenomenon is due to the fact that we continue to see an object for a small fraction of a second after the image of it disappears from the retina. The period of time varies somewhat with different individuals. The so-called "moving" pictures do not move at all. In normal projection 16 brilliant stationary pictures per second appear in succession upon the screen, and during the interval between the pictures the screen is perfectly dark. It is during this period of darkness that the film is jerked forward to get the next picture into position for projection. The eye, however, detects no period of darkness, for on account of persistence of vision it continues to see the stationary picture not only during this period of darkness but dimly for an instant even after the next picture appears upon the screen. This causes the successive stationary pictures, which differ but slightly, to blend smoothly into each other and thus give the effect of actual motion

1 2

3 4

5 6

PHOTOGRAPHS OF SOUND WAVES HAVING THEIR ORIGIN IN AN ELECTRIC SPARK BEHIND THE MIDDLE OF THE BLACK DISK

1. A spherical sound wave. 2. The same wave .00007 second later. 3. A wave reflected from a plane surface, curvature unchanged. 4. A wave reflected from a convex surface, curvature increased. 5. The source at the focus of a SO_2 lens. The photograph shows first, the original wave on the right; second, the reflected wave, with its increased curvature, and third, the transmitted plane wave. 6. Source at focus of a concave mirror; the reflected wave is plane. (Taken by Professor A. L. Foley and Wilmer H. Souder, of the University of Indiana)

its image is just behind it, out to an infinite distance, its image moves back only to the focal plane through F. Hence the image must lie somewhere between F and the mirror. The image $P'Q'$ of an object PQ is always diminished, because it lies between the converging lines PC and QC. It can be located by the ray method (Fig. 419) exactly as in the case of concave lenses. In fact, a convex mirror and a concave lens have exactly the same optical properties. This is because *each always increases the curvature of the incident waves by an amount* $\frac{1}{f}$.

Fig. 420. Real image of candle formed by a concave mirror

448. Images in concave mirrors. Let the images obtainable with a concave mirror be studied precisely as were those obtainable from a convex lens. It will be found that exactly the same series of images is obtained: when the object is between the mirror and the principal focus, the image is virtual, enlarged, and erect; when it is at the focus the reflected waves are plane, that is, the rays from each point are a parallel bundle; when it is between the

Fig. 421. Method of formation of a real image by a concave mirror

principal focus and the center of curvature, the image is inverted, enlarged, and real (Figs. 420 and 421); when it is at a distance R ($= oC$) from the mirror, the image is also at a distance R and of the same size as the object, though inverted; when the object is moved from R out to

a great distance, the image moves from C up to F, and is always real, inverted, and diminished. The most convenient way of finding the focal length is to find where the image of a distant object is formed.

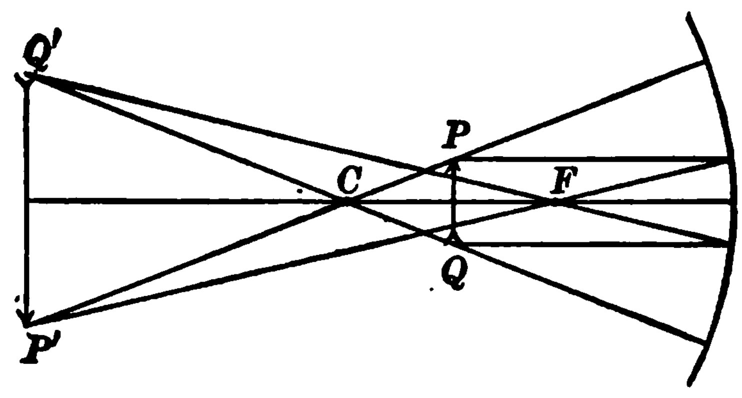


FIG. 422. Ray method of locating real image in a concave mirror

We learn, then, that a concave mirror has exactly the optical properties of a convex lens. This is because, like the convex lens, it always *diminishes* the curvature of the waves. The same formulas hold throughout, and the same constructions are applicable (see Fig. 422).

449. Summary for lenses and spherical mirrors.*

1. Real images, inverted; virtual images, erect.
   The length of all images is given by

$$\frac{L_o}{L_i} = \frac{D_o}{D_i},$$

where L_o and L_i denote the length of object and image respectively, and D_o and D_i their distances from the lens or mirror.

2. Convex lenses and concave mirrors have the same optical properties (always diminish the curvature of the waves).
   a. If object is *more distant* than principal focus, *image is real* and
      (1) *enlarged* when object is between principal focus and twice focal length;
      (2) *diminished* when object is beyond two focal lengths.
   b. If object is *less distant* than principal focus, *image is virtual* and *always enlarged.*
3. Concave lenses and convex mirrors have the same optical properties (always increase the curvature of the waves).
   Image *always virtual* and *diminished* for any position of object.

4. $$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{f}. \qquad (\S\ 439)$$

* Laboratory experiments on the formation of images by concave mirrors and by lenses should follow this discussion. See, for example, Experiments 45 and 46 of the authors' Manual.

This formula may be used in all cases if the following points are borne in mind:

a. D_o is always to be taken as positive.

b. D_i is to be taken as positive for real images and negative for virtual images.

c. f is to be taken as positive for converging systems (convex lenses and concave mirrors) and negative for diverging systems (concave lenses and convex mirrors).

QUESTIONS AND PROBLEMS

1. Show from a construction of the image that a man cannot see his entire length in a vertical mirror unless the mirror is half as tall as he is. Decide from a study of the figure whether or not the distance of the man from the mirror affects the case.

2. A man is standing squarely in front of a plane mirror which is very much taller than he is. The mirror is tipped toward him until it makes an angle of 45° with the horizontal. He still sees his full length. What position does his image occupy?

3. How tall is a tree 200 ft. away if the image of it formed by a lens of focal length 4 in. is 1 in. long? (Consider the image to be formed in the focal plane.)

4. How long an image of the same tree will be formed in the focal plane of a lens having a focal length of 9 in.?

5. What is the difference between a real and a virtual image?

6. When does a convex lens form a real, and when a virtual, image? When an enlarged, and when a diminished, image? When an erect, and when an inverted, one?

7. When a camera is adjusted to photograph a distant object, what change in the length of the bellows must be made to photograph a near object? Explain clearly why this adjustment is necessary.

8. Rays diverge from a point 20 cm. in front of a converging lens whose focal length is 4 cm. At what point do the rays come to a focus?

9. An object 2 cm. long was placed 10 cm. from a converging lens and the image was formed 40 cm. from the lens on the other side. Find the focal length of the lens and the length of the image.

10. An object is 15 cm. in front of a convex lens of 12 cm. focal length. What will be the nature of the image, its size, and its distance from the lens?

11. Why does the nose appear relatively large in comparison with the ears when the face is viewed in a convex mirror?

12. Can a convex mirror ever form an inverted image? Why?

OPTICAL INSTRUMENTS

450. The photographic camera. A fairly distinct, though dim, image of a candle flame can be obtained with nothing more elaborate than a pinhole in a piece of cardboard (Fig. 423). If the receiving screen is replaced by a photographic plate, the arrangement becomes a *pinhole camera*, with which good pictures may be taken if the exposure is sufficiently long. If we try to increase the brightness of the image by enlarging the hole, the image becomes blurred, because the narrow pencils $a_1a'_1$, $a_2a'_2$, etc. become cones whose bases a'_1, a'_2, overlap and thus destroy the distinctness of the outline.

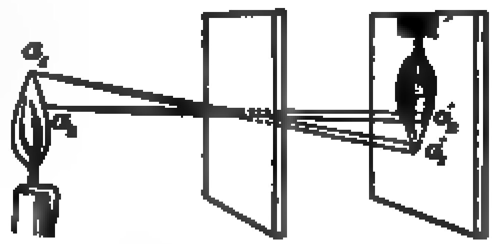


FIG. 423. Image formed by a small opening

It is possible, without sacrificing distinctness of outline, to gain the increased brightness due to the larger hole by placing a lens in the hole (Fig. 424). If the receiving screen is now a sensitive plate, the arrangement becomes a *photographic camera* (Fig. 425). But while with the pinhole camera the screen may be at any distance from the hole, with a lens the plate and the object must be at conjugate foci of the lens.

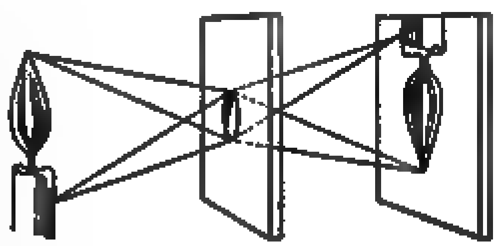


FIG. 424. Principle of the photographic camera

Let a lens of, say, 4 feet focal length be placed in front of a hole in the shutter of a darkened room, and a semitransparent screen (for example, architect's tracing paper) placed at the focal plane. A perfect reproduction of the opposite landscape will appear.

FIG. 425. The photographic camera

451. The projecting lantern. The projecting lantern is essentially a camera in which the position of object and image have been interchanged; for in the use of the camera the object is at a considerable distance, and a small inverted image is formed on a plate placed somewhat farther from the lens than the focal distance. In the use of the projecting lantern the object *P* (Fig. 426) is placed a trifle farther from the lens *L'* than its focal length, and an enlarged inverted image is formed on

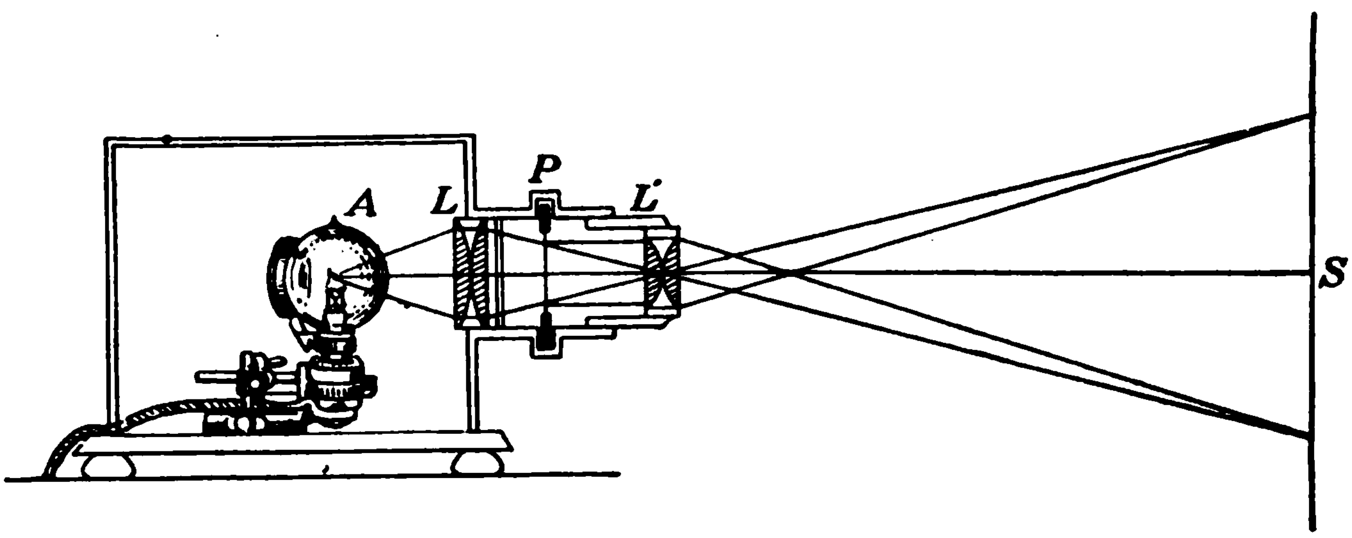


FIG. 426. The projecting lantern (stereopticon)

a distant screen *S*. In both instruments the optical part is simply a convex lens, or a combination of lenses which is equivalent to a convex lens.

The object *P*, whose image is formed on the screen, is usually a transparent slide which is illuminated by a powerful light *A*. The image is as many times larger than the object as the distance from *L'* to *S* is greater than the distance from *L'* to *P*. The light *A* is usually either an incandescent lamp or an electric arc. The moving-picture projector employs a long film of small "positives" which moves swiftly between the condensing lens *L* and the projecting lens *L'* (see opposite p. 386).

The above are the only essential parts of a projecting lantern. In order, however, that the slide may be illuminated as brilliantly as possible, a so-called condensing lens *L* is always used. This concentrates light upon the transparency and directs it toward the screen.

In order to illustrate the principle of the instrument, let a beam of sunlight be reflected into the room and fall upon a lantern slide. When a lens is placed a trifle more than its focal distance in front of the slide, a brilliant picture will be formed on the opposite wall.

452. The eye. The eye is essentially a camera in which the cornea *C* (Fig. 427), the aqueous humor *l*, and the crystalline lens *o* act as one single lens which forms an inverted image *P'Q'* on the retina, an expansion of the optic nerve covering the inside of the back of the eyeball.

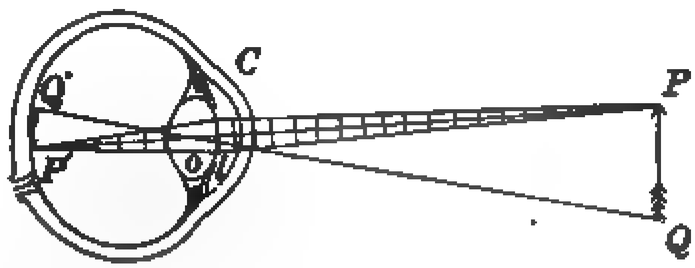


Fig. 427. The human eye

In the case of the camera the images of objects at different distances are obtained by placing the plate nearer to or farther from the lens. In the eye, however, the distance from the retina to the lens remains constant, and the adjustment for different distances is effected by changing the focal length of the lens system in such a way as always to keep the image upon the retina. Thus, when the normal eye is perfectly

1 2

Fig. 428. The pupil dilates when the light is dim and contracts when it is intense

relaxed, the lens has just the proper curvature to focus plane waves upon the retina, that is, to make distant objects distinctly visible. But by directing attention upon near objects we cause the muscles which hold the lens in place to contract

in such a way as to make the lens more convex, and thus bring into distinct focus objects which may be as close as eight or ten inches. This power of adjustment or *accommodation*, however, varies greatly in different individuals.

The iris, or colored part of the eye, is a diaphragm which varies the amount of light which is admitted to the retina (Figs. 428, (1) and (2)).

453. Nearsightedness and farsightedness. In a *normal* eye, provided the lens is relaxed and resting, parallel rays come to a focus *on* the retina (Fig. 429, (1)); in a *nearsighted* eye they focus *in front of* the retina (Fig. 429, (2)); and in a *farsighted* eye they reach the retina *before coming to a focus* (Fig. 429, (3)).

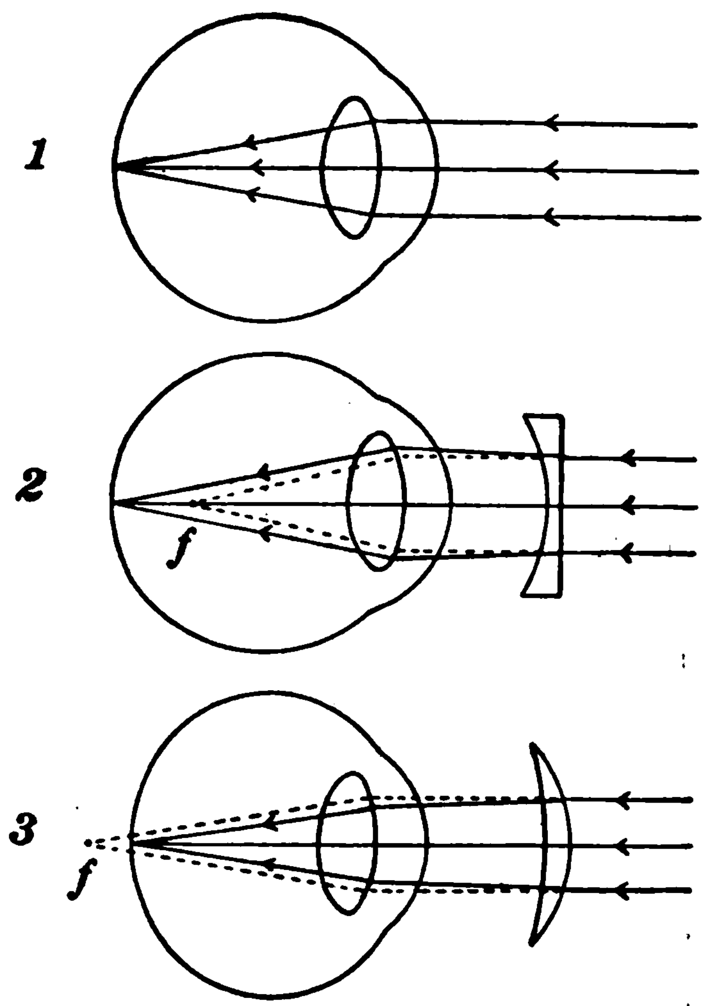


FIG. 429. Defects of vision

Those who are nearsighted can see distinctly only those objects which are near. The usual reason for nearsightedness is that the retina is too far from the lens. The diverging lens corrects this defect of vision because it makes the rays from a distant object enter the eye as if they had come from an object near by; that is, it partially counteracts the converging effect of the eye (Fig. 429 (2)).

Those who are farsighted cannot *when the lens is relaxed* see distinctly even a very distant object. The usual reason for farsightedness is that the eyeball is too short from lens to retina. The rays from *near* objects are converged, or focused, towards *f* behind the retina in spite of all effort at accommodation. A converging lens gives distinct vision because

it supplements the converging effect of the eye (Fig. 429, (3)). In old age the lens loses its power of accommodation, that is, the ability to become more convex when looking at a near object; hence, in old age a normal eye requires the same sort of lens as is used in true farsightedness.

454. The apparent size of a body. The apparent size of a body depends simply upon the size of the image formed upon the retina by the lens of the eye, and hence upon the size of *the visual angle* pCq (Fig. 430). The size of this angle evidently increases as the object is brought nearer to the eye (see PCQ). Thus, the image formed on the retina when a man is 100 feet from the eye is in reality only one tenth as large as the image formed of the same man when he is but 10 feet away. We do not actually interpret the larger image as representing a larger man simply because we have been taught by lifelong experience to take account of the known distance of an object in forming our estimate of its actual size. To an infant who has not yet formed ideas of distance the man 10 feet away doubtless appears ten times as large as the man 100 feet away.

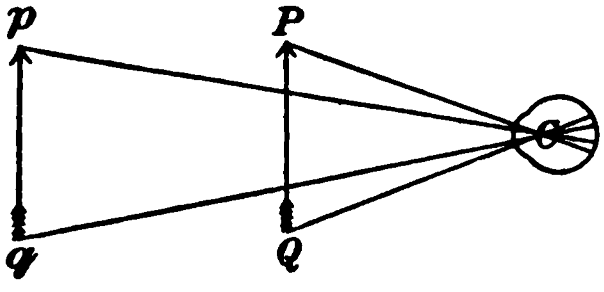


Fig. 430. The visual angle

455. Distance of most distinct vision. When we wish to examine an object minutely, we bring it as close to the eye as possible in order to increase the size of the image on the retina. But there is a limit to the size of the image which can be produced in this way; for when the object is brought nearer to the normal eye than about 10 inches, the curvature of the incident wave becomes so great that the eye lens is no longer able, without too much strain, to thicken sufficiently to bring the image into sharp focus upon the retina. Hence a person with normal eyes holds an object which he wishes to see as distinctly as possible at a distance of about 10 inches.

Although this so-called *distance of most distinct vision* varies somewhat with different people, for the sake of having a standard of comparison in the determination of the magnifying powers of optical instruments some exact distance had to be chosen. The distance so chosen is 10 inches, or 25 centimeters.

456. Magnifying power of a convex lens. If a convex lens is placed immediately before the eye, the object may be brought much closer than 25 centimeters without loss of distinctness, for the curvature of the wave is partly or even wholly overcome by the lens before the light enters the eye.

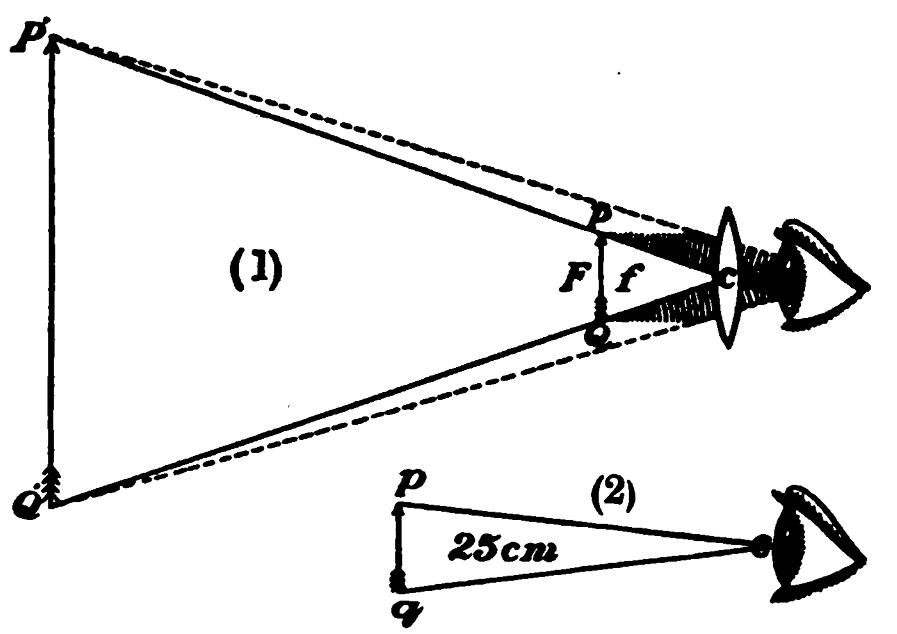


FIG. 431. Magnifying power of a lens

If we wish to use a lens as a magnifying glass to the best advantage, we place the eye *as close to it as we can*, so as to gather as large a cone of rays as possible, and then place the object at a distance from the lens *equal to its focal length*, so that the waves after passing through it are plane. They are then focused by the eye with the least possible effort. The visual angle in such a case is PcQ (Fig. 431,(1)); for, since the emergent waves are plane, the rays which pass through the center of the eye from P and Q are parallel to the lines through Pc and Qc. But if the lens were not present, and if the object were 25 centimeters from the eye, the visual angle would be the small angle pcq (Fig. 431, (2)). The magnifying power of a simple lens is due, therefore, to the fact that by its use an object can be viewed distinctly when held closer to the eye than is otherwise possible. This condition gives a visual angle that increases the size of the image on the retina.

The less the focal length of the lens, the nearer to it may the object be placed, and therefore the greater the visual angle, or magnifying power.

The ratio of the two angles PcQ and pcq is approximately $25/f$, where f is the focal length of the lens expressed in centimeters. Now *the magnifying power of a lens or microscope is defined as the ratio of the angle actually subtended by the image when viewed through the instrument, to the angle subtended by the object when viewed with the unaided eye at a distance of 25 centimeters.* Therefore the magnifying power of a simple lens is $25/f$. Thus, if a lens has a focal length of 2.5 centimeters, it produces a magnification of 10 diameters when the object is placed at its principal focus. If the lens has a focal length of 1 centimeter, its magnifying power is 25, etc.

457. Magnifying power of an astronomical telescope. In the astronomical telescope the *objective*, or forward lens, forms *at its principal focus* an image $P'Q'$ of an object PQ which is usually very distant. This image

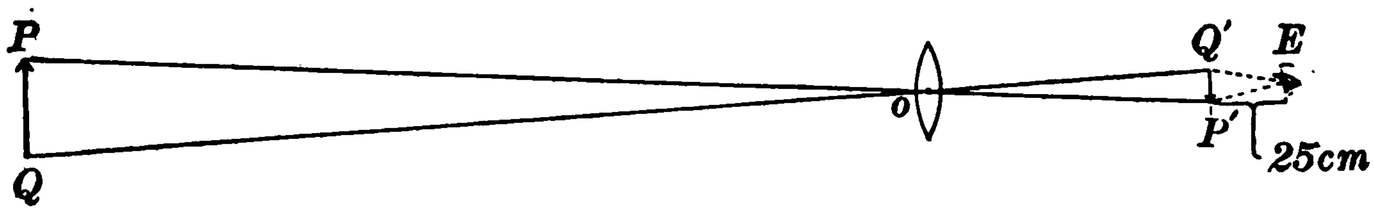


FIG. 432. The magnifying power of a telescope objective is $F/25$

may be viewed by the unaided eye at a distance of 25 cm. (Fig. 432). The focal length of the objective is usually very much longer than 25 cm. (about 2000 cm. in the case of the great Yerkes telescope shown opposite p. 365), so that the visual angle $P'EQ'$ is increased by means of the objective alone, the increase being $F/25$*, that is, in direct proportion to its focal length.

In practice, however, the image is not viewed with the unaided eye, but with a simple magnifying glass called an *eyepiece* (Fig. 433), placed so that the image is at its focus. Since we have seen in § 456 that the simple magnifying glass increases the visual angle $25/f$ times, f being the focal length of the eyepiece, it is clear that the total magnification

*The angle PoQ = angle $P'oQ'$. Consider the short line $Q'P'$ as an arc, and the angles $Q'EP'$ and $Q'oP'$ are inversely proportional to their radii, F and 25.

produced by both lenses, used as above, is $F/25 \times 25/f = F/f$. *The magnifying power of an astronomical telescope is therefore the focal length of the objective divided by the focal length of the eyepiece.* It will be seen, therefore, that to get a high magnifying power it is necessary to use an objective of as great focal length as possible and an eyepiece of as short focal length as possible. The focal length of the great lens at the Yerkes Observatory is about 62 feet, and its diameter 40 inches. The great diameter enables it to collect a very large amount of light, which makes celestial objects more plainly visible.

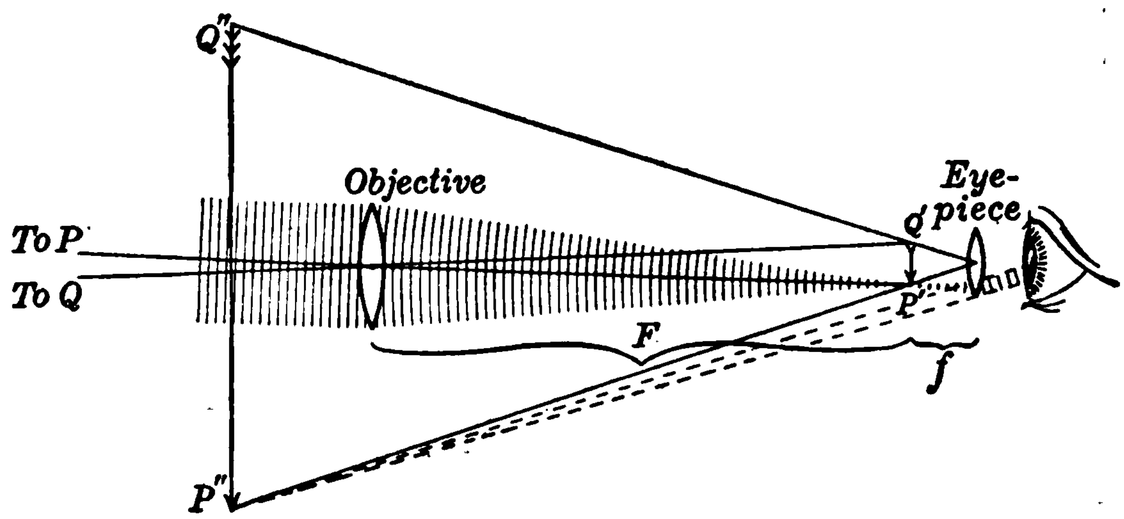


FIG. 433. The magnifying power of a telescope is F/f

Eyepieces often have focal lengths as small as $\frac{1}{4}$ inch. Thus, the Yerkes telescope, when used with a $\frac{1}{4}$-inch eyepiece, has a magnifying power of 2976.

458. The magnifying power of the compound microscope. The compound microscope is like the telescope in that the front lens, or *objective*, forms a real image of the object at the focus of the eyepiece. The size of the image $P'Q'$ (Fig. 434) formed by the objective is as many times the size of the object PQ as v, the distance from the objective to the image, is times u, the distance from the objective to the object (see § 441). Since the eyepiece magnifies this image $25/f$ times, the total magnifying power of a compound microscope is $\frac{v}{u}\frac{25}{f}$. Ordinarily v is practically the length L of the microscope tube, and u is the focal length F of the objective. Wherever this is the case, then, the magnifying power of the compound microscope is $\frac{25\,L}{Ff}$.

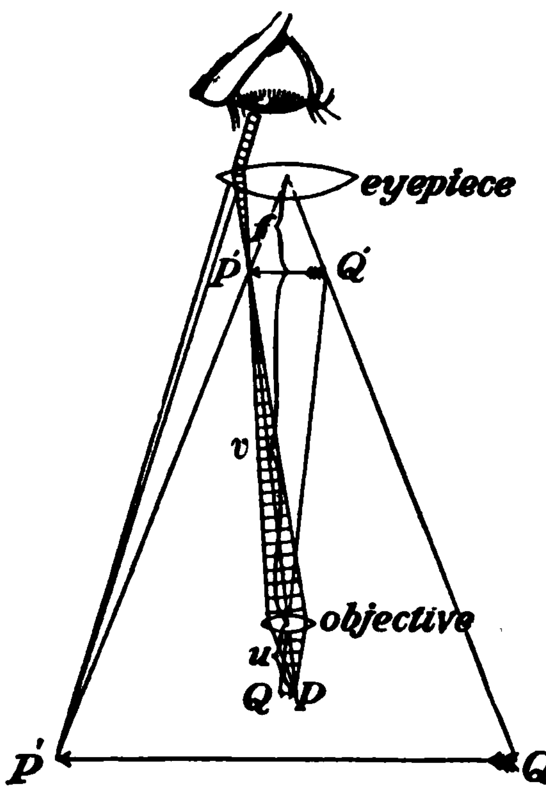


FIG. 434. The compound microscope

The relation shows that in order to get a high magnifying power with a compound microscope the focal length of both eyepiece and objective should be as short as possible, while the tube length should be as long as possible. Thus, if a microscope has both an eyepiece and an objective of 6 millimeters focal length and a tube 15 centimeters long, its magnifying power will be $\frac{25 \times 15}{.6 \times .6} = 1042$. Magnifications as high as 2500 or 3000 are sometimes used, but it is impossible to go much farther, for the reason that the image becomes too faint to be seen when it is spread over so large an area.

459. The opera glass. On account of the large number of lenses which must be used in the terrestrial telescope, it is too bulky and awkward for many purposes, and hence it is often replaced by the opera glass (Fig. 435). This instrument consists of an objective like that of

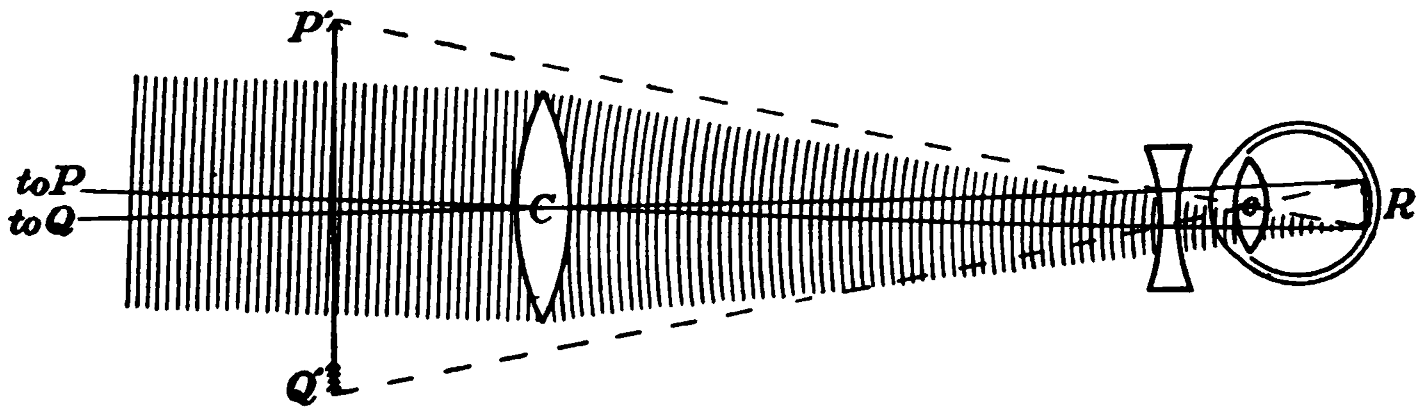


FIG. 435. The opera glass

the telescope, and an eyepiece which is a concave lens of the same focal length as the eye of the observer. The effect of the eyepiece is therefore to just neutralize the lens of the eye. Hence the objective, in effect, forms its image directly upon the retina. It will be seen that the size of the image formed upon the retina by the objective of the opera glass is as much greater than the size of the image formed by the naked eye as the focal length CR of the objective is greater than the focal length cR of the eye. Since the focal length of the eye is the same as that of the eyepiece, *the magnifying power of the opera glass, like that of the astronomical telescope, is the ratio of the focal lengths of the objective and eyepiece.* Objects seen with an opera glass appear erect, since the image formed on the retina is inverted, as is the case with images formed by the lens of the eye unaided.

460. The stereoscope. Binocular vision. When an object is seen with both eyes, the images formed on the two retinas differ slightly, because of the fact that the two eyes, on account of their lateral separation, are viewing the object from slightly different angles. It is this difference

in the two images which gives to an object or landscape viewed with two eyes an appearance of depth, or solidity, which is wholly wanting when one eye is closed. The stereoscope is an instrument which reproduces in photographs this effect of binocular vision. Two photographs of the same object are taken from slightly different points of view. These photographs are mounted at A and B (Fig. 436), where they are simultaneously viewed by the two eyes through the two prismatic lenses m and n. These two lenses superpose the two images at C because of their action as prisms, and at the same time magnify them because of their action as simple magnifying lenses. The result is that the observer is conscious of viewing but one photograph; but this differs from ordinary photographs in that, instead of being flat, it has all of the characteristics of an object actually seen with both eyes.

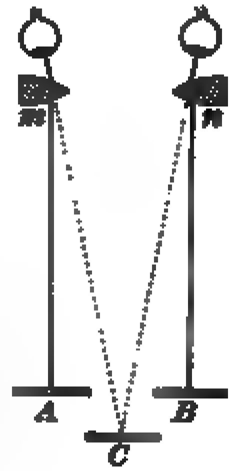


FIG. 436. Principle of the stereoscope

The opera glass has the advantage over the terrestrial telescope of affording the benefit of binocular vision; for while telescopes are usually constructed with one tube, opera glasses always have two, one for each eye.

461. The Zeiss binocular. The greatest disadvantage of the opera glass is that the field of view is very small. The terrestrial telescope has a larger field but is of inconvenient length. An instrument called the Zeiss binocular (Fig. 437) has recently come into use, which combines the compactness of the opera glass with the wide field of view of the terrestrial telescope. The compactness is gained by causing the light to pass back and forth through total reflecting prisms, as in the figure. These reflections also perform the function of reinverting the image, so that the real image which is formed at the focus of the eyepiece is erect. It will be seen, therefore, that the instrument is essentially an astronomical telescope in which the image is reinverted by reflection, and in which the tube is shortened by letting the light pass back and forth between the prisms.

FIG. 437. The Zeiss binocular

A further advantage which is gained by the Zeiss binocular is due to the fact that the two objectives are separated by a distance which is greater than the distance between the eyes, so that the stereoscopic effect is more prominent than with the unaided eye or with the ordinary opera glass.*

462. The periscope. A periscope is a sort of double-jointed telescope which makes use of total reflection twice, — at the top and at the bottom. The system of lenses gives a magnification of about $1\frac{1}{2}$ diameters, as

Fig. 438. A parabolic reflector

this has been found best to make ships appear at their true distances from the submarine. There is no stereoscopic effect, since the periscope is not double like a binocular.

463. Parabolic reflectors. For the projection of a more nearly cylindrical beam than is possible with spherical mirrors, it is customary to use parabolic reflectors, as in automobile headlights (Fig. 438, (1) and (2)). The light is placed a little closer to the reflector than the principal focus, so that the reflected light may spread somewhat. The same principle is employed in searchlights, except that the source of light (usually a powerful arc) is kept more nearly at the principal focus of the reflector. The Sperry 60-inch searchlight, the most powerful in the world, has a beam candle power of approximately two thirds that of the sun, and its light is plainly visible at a distance of one hundred miles.

* Laboratory experiments on the magnifying powers of lenses and on the construction of microscopes and telescopes should follow this chapter. See for example, Experiments 47, 48, and 49 of the authors' Manual.

QUESTIONS AND PROBLEMS

1. Why is it necessary for the pupils of your eyes to be larger in a dim cellar than in the sunshine? Why does the photographer use a large stop on dull days in photographing moving objects?

2. If a photographer wishes to obtain the full figure on a plate of cabinet size, does he place the subject nearer to or farther from the camera than if he wishes to take the head only? Why?

3. A child 3 ft. in height stood 15 ft. from a camera whose lens had a focal length of 18 in. What was the distance from the lens to the photographic plate and the length of the child's photograph?

4. If 20 sec. is the proper length of exposure when you are printing photographs by a gas light 8 in. from the printing frame, what length of exposure would be required in printing from the same negative at a distance of 16 in. from the same light?

5. If a 20-second exposure is correct at a distance of 6 in. from an 8-candle-power electric light, what is the required time of exposure at a distance of 12 in. from a 32-candle-power electric light?

6. The image, on the retina, of a book held a foot from the eye is larger than that of a house on the opposite side of the street. Why do we not judge that the book is actually larger than the house?

7. What sort of lenses are necessary to correct shortsightedness? longsightedness? Explain with the aid of a diagram.

8. What is the magnifying power of a $\frac{1}{4}$-in. lens used as a simple magnifier?

9. If the length of a microscope tube is increased after an object has been brought into focus, must the object be moved nearer to or farther from the lens in order that the image may again be in focus?

10. Explain as well as you can how a telescope forms the image that you see when you look into it.

11. Is the image on the retina erect or inverted?

CHAPTER XX

COLOR PHENOMENA

Color and Wave Length

464. Wave lengths of different colors. Let a soap film be formed across the top of an ordinary drinking glass, care being taken that both the solution and the glass are as clean as possible. Let a beam of sunlight or the light from a projecting lantern pass through a piece of red glass at A, fall upon the soap film F, and be reflected from it to a white screen S (see Fig. 439). Let a convex lens L of from 6 to 12 inches focal length be placed in the path of the reflected beam in such a position as to produce an image of the film upon the screen S, that is, in such a position that film and screen are at conjugate foci of the lens. The system of red and black bands upon the screen is formed precisely as in § 427, by the interference of the two beams of light coming from the front and back surfaces of the wedge-shaped film. Now let the red glass be held in one half of the beam and a piece of green glass in the other half, the two pieces being placed edge to edge, as shown at A. Two sets of fringes will be seen side by side on the screen. The fringes will be red and black on one side of the image, and green and black on the other; but it will be noticed at once that the dark bands on the green side are closer together than the dark bands on the other side; in

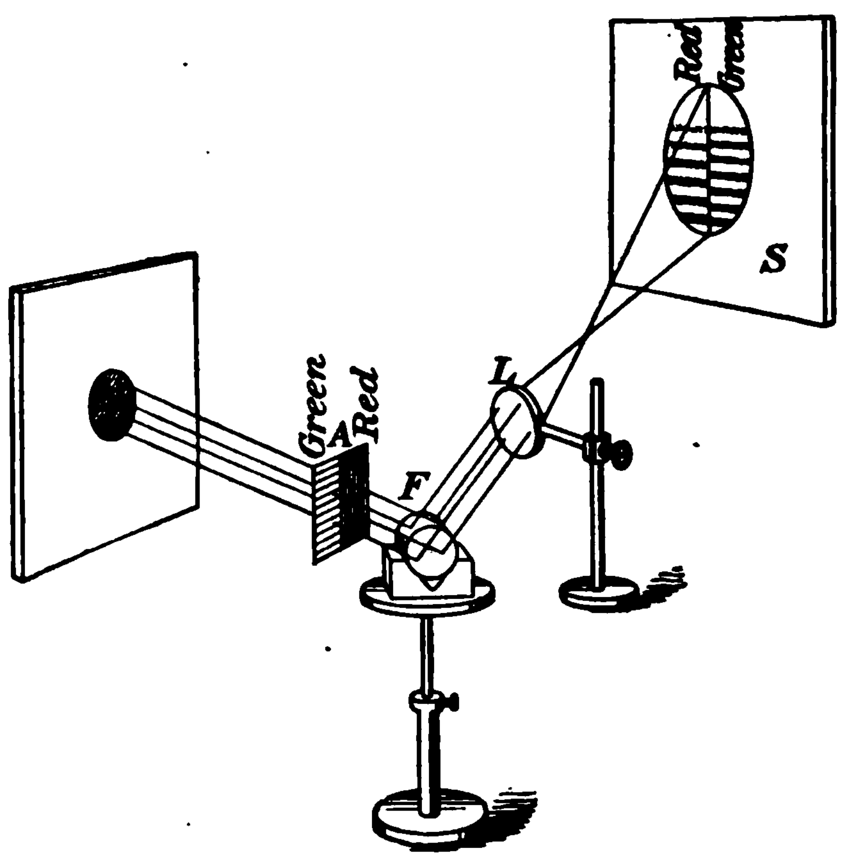


Fig. 439. Projection of soap-film fringes

fact, seven fringes on the side of the film which is covered by the green glass will be seen to cover about the same distance as six fringes on the red side.*

Since it was shown in Fig. 390 that the distance between two dark bands corresponds to an increase of one-half wave length in the thickness of the film, we conclude, from the fact that the dark bands on the red side are farther apart than those on the green side, that red light must have a longer wave length than green light. The wave length of the central portion of each colored region of the spectrum is roughly as follows:

Red	.000068 cm.	Green	.000052 cm.
Yellow	.000058 cm.	Blue	.000046 cm.
Violet	.000042 cm.		

Let the red and green glasses be removed from the path of the beam. The red and green fringes will be seen to be replaced by a series of bands brilliantly colored in different hues. These are due to the fact that the lights of different wave length form interference bands at different places on the screen. Notice that the upper edges of the bands (lower edges in the inverted image) are reddish, while the lower edges are bluish. We shall find the explanation of this fact in § 473.

465. Composite nature of white light. Let a beam of sunlight pass through a narrow slit and fall on a prism, as in Fig. 440. The beam which enters the prism as white light is dispersed into red, yellow, green, blue, and violet lights, although each color merges, by insensible gradations, into the next. This band of color is called a *spectrum.*

FIG. 440. White light decomposed by a prism

We conclude from this experiment that *white light is a mixture of all the colors of the spectrum, from red to violet inclusive.*

* The experiment may be performed at home by simply looking through red and green glasses at a soap film so placed as to reflect white light to the eye.

466. Color of bodies in white light. Let a piece of red glass be held in the path of the colored beam of light in the experiment of the preceding section. All the spectrum except the red will disappear, thus showing that all the wave lengths except red have been absorbed by the glass. Let a green glass be inserted in the same way. The green portion of the spectrum will remain strong, while the other portions will be greatly enfeebled. Hence green glass must have a much less absorbing effect upon wave lengths which correspond to green than upon those which correspond to red and blue. Let the green and red glasses be held one behind the other in the path of the beam. The spectrum will almost completely vanish, for the red glass has absorbed all except the red rays, and the green glass has absorbed these.

We conclude, therefore, that the color which a body has in ordinary daylight is determined by the wave lengths which the body has *not* the power of absorbing. Thus, if a body appears white in daylight, it is because it diffuses or reflects all wave lengths equally to the eye, and does not absorb one set more than another. For this reason the light which comes from it to the eye is of the same composition as daylight or sunlight. If, however, a body appears red in daylight, it is because it absorbs the red rays of the white light which falls upon it less than it absorbs the others, so that the light which is diffusely reflected contains a larger proportion of red wave lengths than is contained in ordinary light. Similarly, a body appears yellow, green, or blue when it absorbs less of one of these colors than of the rest of the colors contained in white light, and therefore sends a preponderance of some particular wave length to the eye.

467. Color of bodies placed in colored lights. Let a body which appears white in sunlight be placed in the red end of the spectrum. It will appear to be red. In the blue end of the spectrum it will appear to be blue, etc. This confirms the conclusion of the last paragraph, that a white body has the power of diffusely reflecting all the colors of the spectrum equally.

Next let a skein of red yarn be held in the blue end of the spectrum. It will appear nearly black. In the red end of the spectrum

it will appear strongly red. Similarly, a skein of blue yarn will appear nearly black in all the colors of the spectrum except blue, where it will have its proper color.

These effects are evidently due to the fact that the red yarn, for example, has the power of diffusely reflecting red wave lengths copiously, but of absorbing, to a large extent, the others. Hence, when held in the blue end of the spectrum, it sends but little color to the eye, since no red light is falling upon it.

Soak a handful of asbestos or cotton batting in a saturated salt solution; squeeze out most of the brine; pour over the material a quantity of strong alcohol. When ignited, this will produce a large flame of almost pure-yellow light. In a darkened room allow the yellow light to fall strongly upon a spectrum chart of six colors. The only color on the chart that appears natural is the yellow.

468. Compound colors. It must not be inferred from the preceding paragraphs that every color except white has one definite wave length, for the same effect may be produced on the eye by a mixture of several different wave lengths as is produced by a single wave length. This statement may be proved by the use of an apparatus known as Newton's color disk (Fig. 441). The arrangement makes it possible to rotate differently colored sectors so rapidly before the eye that the effect is precisely the same as though the colors came to the eye simultaneously. If one half of the disk is red and the other half green, the rotating disk will appear yellow, the color being very similar to the yellow of the spectrum. If green and violet are mixed in the same way, the result will be light blue. Although the colors produced in this way are not distinguishable by the eye

FIG. 441. Newton's color disk

from spectral colors, it is obvious that their physical constitution is wholly different; for while a spectral color consists of waves of a single wave length, the colors produced by mixture are compounds of several wave lengths. For this reason the spectral colors are called pure and the others compound. In order to tell whether the color of an object is pure or compound, it is only necessary to observe it through a prism. If it is compound, the colors will be separated, giving an image of the object for each color. If it is pure, the object will appear through the prism exactly as it does without the prism.

By compounding colors in the way described above we can produce many which are not found in the spectrum. Thus, mixtures of red and blue give purple or crimson; mixtures of black with red, orange, or yellow give rise to the various shades of brown. Lavender may be formed by adding three parts of white to one of blue; lilac, by adding to fifteen parts of white four parts of red and one of blue; olive, by adding one part of black to two parts of green and one of red.

469. Complementary colors. Since white light is a combination of all the colors from red to violet inclusive, it might be expected that if one or several of these colors were subtracted from white light, the residue would be colored light.

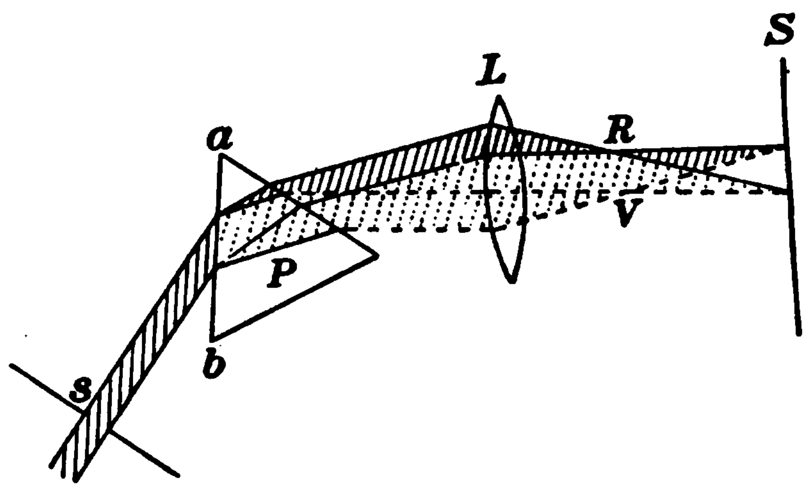


FIG. 442. Recombination of spectral colors into white light

To test this experimentally let a beam of sunlight be passed through a slit *s*, a prism *P*, and a lens *L*, to a screen *S*, arranged as in Fig. 442. A spectrum will be formed at *RV*, the position conjugate to the slit *s*, and a pure white spot will appear on the screen when it is at the position which is conjugate to the prism face *ab*. Let a card be slipped into the path of the

beam at R, so as to cut off the red portion of the light. The spot on S will appear a brilliant shade of greenish blue. This is the compound color left after red is taken from the white light. This shade of blue is therefore called the *complementary color* of the red which has been subtracted. Two *complementary colors* are therefore defined as any two colors which produce white when added to each other.

Let the card be slipped in from the side of the blue rays at V. The spot will first take on a yellowish tint when the violet alone is cut out; and as the card is slipped farther in, the image will become a deep shade of red when violet, blue, and part of the green are cut out.

Next let a lead pencil be held vertically between R and V so as to cut off the middle part of the spectrum; that is, the yellow and green rays. The remaining red, blue, and violet will unite to form a brilliant purple. In each case the color on the screen is the complement of that which is cut out.

470. Retinal fatigue. Let the gaze be fixed intently for not less than twenty or thirty seconds on a point at the center of a block of any brilliant color — for example, red. Then look off at a dot on a white wall or a piece of white paper, and hold the gaze fixed there for a few seconds. The brilliantly colored block will appear on the white wall, but its color will be the *complement* of that first looked at.

The explanation of this phenomenon, due to so-called "retinal fatigue," is found in the fact that although the white surface is sending waves of all colors to the eye, the nerves which responded to the color first looked at have become fatigued, and hence fail to respond to this color when it comes from the white surface. Therefore the sensation produced is that due to white light minus this color; that is, to the complement of the original color. A study of the spectral colors by this method shows that the following colors are complementary.

Red	Orange	Yellow	Violet	Green
Bluish green	Greenish blue	Blue	Greenish yellow	Crimson

471. Color of pigments. When yellow light is added to the proper shade of blue, white light is produced, since these colors are complementary. But if a yellow pigment is added to a blue one, the color of the mixture will be green. This is

because the yellow pigment removes the blue and violet by absorption, and the blue pigment removes the red and yellow, so that only green is left.

When pigments are mixed, therefore, each one *subtracts* certain colors from white light, and the color of the mixture is that color which escapes absorption by the different ingredients. Adding *pigments* and adding *colors*, as in § 468, are therefore wholly dissimilar processes and produce widely different results.

472. Three-color printing. It is found that all colors can be produced by suitably mixing with the color disk (Fig. 441) three spectral colors, namely red, green, and blue-violet. These are therefore called the *three primary colors.* The so-called primary pigments are simply the complements of these three primary colors. They are, in order, peacock blue, crimson, and light yellow. The three primary colors when mixed yield white. The three primary pigments when mixed yield black, because together they subtract all the ingredients from white light. The process of three-color printing consists in mixing on a white background, that is, on white paper, the three primary *pigments* in the following way: Three different photographs of a given-colored object are taken, each through a *filter* of gelatin stained the color of one of the primary colors. From these photographs halftone "blocks" are made in the usual way. The colored picture is then made by carefully superposing prints from these blocks, using with each an ink whose color is the complement of that of the "filter" through which the original negative was taken. The plate on the opposite page illustrates fully the process. It will be interesting to examine differently colored portions with a lens of moderate magnifying power.

473. Colors of thin films. The study of complementary colors has furnished us with the key to the explanation of the fact, observed in § 464, that the upper edge of each colored band produced by the water wedge is reddish, while the lower edge

THREE-COLOR PRINTING

1, yellow impression (negative made through a blue-violet filter); 2, crimson impression (negative made through a green filter); 3, crimson on yellow; 4, blue impression (negative made through a red filter); 5, yellow, crimson, and blue combined (the final product). The circles at the right show the colors of ink used in making each impression. Notice the different colors in 5, which are made by combining yellow, crimson, and blue

is bluish. The red on the upper edge is due to the fact that there the shorter blue waves are destroyed by interference and a complementary red color is left; while on the lower edge of each fringe, where the film is thicker, the longer red waves interfere, leaving a complementary blue. In fact, each wave length of the incident light produces a set of fringes, and it is the superposition of these different sets which gives the resultant colored fringes. Where the film is too thick the overlapping is so complete that the eye is unable to detect any trace of color in the reflected light.

In films which are of uniform thickness, instead of wedge-shaped, the color is also uniform, so long as the observer does not change the angle at which the film is viewed. With any change in this angle the thickness of film through which the light must pass in coming to the observer changes also, and hence the color changes. This explains the beautiful play of iridescent colors seen in soap bubbles, thin oil films, mother of pearl, etc.

474. Chromatic aberration. It has heretofore been assumed that all the waves which fall on a lens from a given source are brought to one and the same focus. But since blue rays are bent more than red ones in passing through a prism, it is clear that in passing through a lens the blue light must be brought to a focus at some point v (Fig. 443) nearer to the lens than r, where the red light is focused, and that the foci for intermediate colors must fall in intermediate positions. It is for this reason that an image formed by a simple lens is always fringed with color.

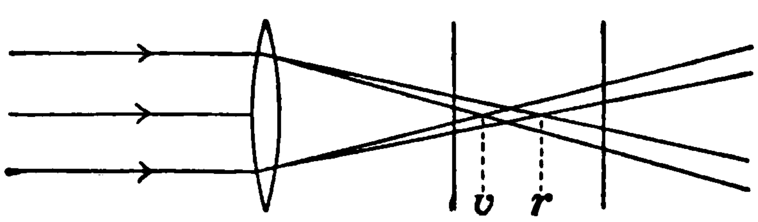


FIG. 443. Chromatic aberration in a lens

Let a card be held at the focus of a lens placed in a beam of sunlight (Fig. 443). If the card is slightly nearer the lens than the focus, the spot of light will be surrounded by a red fringe, for the red rays, being

least refracted, are on the outside. If the card is moved out beyond the focus, the red fringe will be found to be replaced by a blue one; for after crossing at the focus it will be the more refrangible rays which will then be found outside.

This dispersion of light produced by a lens is called *chromatic aberration.*

475. Achromatic lenses. The color effect caused by the chromatic aberration of a simple lens greatly impairs its usefulness. Fortunately, however, it has been found possible to eliminate this effect almost completely by combining into one lens a convex lens of crown glass and a concave lens of flint glass (Fig. 444). The first lens then produces both bending and dispersion, while the second almost completely overcomes the dispersion without entirely overcoming the bending. Such lenses are called *achromatic lenses.* The first one was made by John Dollond in London in 1758. They are used in the construction of all good telescopes and microscopes.

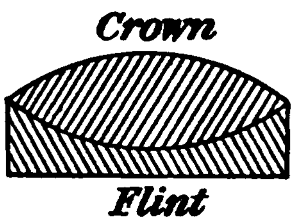


FIG. 444. An achromatic lens

QUESTIONS AND PROBLEMS

1. What determines the color of an opaque body? a transparent body? What is the appearance of a bunch of green grass when seen by pure red light? Explain.

2. What is "white"? What is "black"? Explain why a block of ice is transparent while snow is opaque and white.

3. Why do white bodies look blue when seen through a blue glass?

4. What color would a yellow object appear to have if looked at through a blue glass? (Assume that the yellow is a pure color.)

5. A gas flame is distinctly yellow as compared with sunlight. What wave lengths, then, must be comparatively weak in the spectrum of a gas flame?

6. Why does dark blue appear black by candle light?

7. Certain blues and greens cannot be distinguished from each other by candle light. Explain.

8. Does blue light travel more slowly or faster in glass than red light? How do you know?

Spectra

476. The rainbow. There is formed in nature a very beautiful spectrum with which everyone is familiar — the *rainbow.*

Let a spherical bulb F (Fig. 445) $1\frac{1}{2}$ or 2 inches in diameter be filled with water and held in the path of a beam of sunlight which enters the room through a hole in a piece of cardboard AB. A miniature rainbow will be formed on the screen around the opening, the violet edge of the bow being toward the center of the circle and the red outside. A beam of light which enters the flask at C is there both refracted and dispersed; at D it is totally reflected; and at E it is again refracted and dispersed on passing out into the air. Since in both of the refractions the violet is bent more than the red, it is obvious that it must return nearer to the direction of the incident beam than the red rays. If the flask were a perfect sphere, the angle included between the incident ray OC and the emergent red ray ER would be 42°; and the angle between the incident ray and the emergent violet ray EV would be 40°.

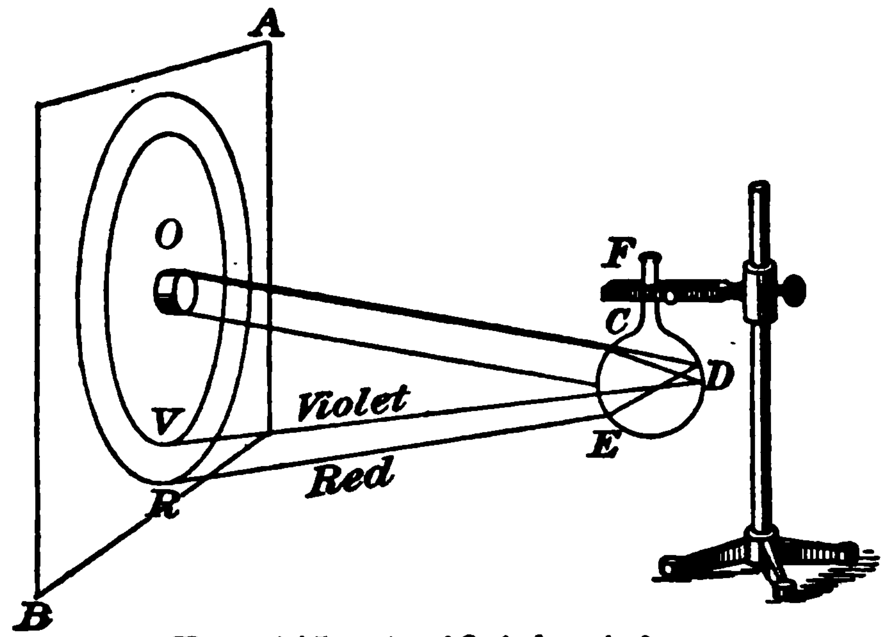


FIG. 445. Artificial rainbow

The actual rainbow seen in the heavens is due to the refraction and reflection of light in the drops of water in the air, which act exactly as did the flask in the preceding experiment. If the observer is standing at E with his back to the sun, the light which comes from the drops so as to make an angle of 42° (Fig. 446) with the line drawn from the observer to the sun must be red light; while the light which comes from drops which are at an angle of 40° from the eye must be violet light. In direct sunshine the prismatic color seen in a dewdrop changes to another color when the head is shifted sidewise. It is clear that those drops

whose direction from the eye makes any particular angle with the line drawn from the eye to the sun must lie on a circle whose center is on that line. Hence we see a circular arc of light which is violet on the inner edge and red on the outer edge. A second bow having the red on the inside and the violet on the outside is often seen outside of the one just described, and concentric with it. This bow arises from rays which have suffered two internal reflections and two refractions, in the manner shown in Fig. 446.

FIG. 446. Primary and secondary rainbows

477. Continuous spectra. Let a Bunsen burner arranged to produce a white flame be placed behind a slit *s* (Fig. 447). Let the slit be viewed through a prism *P*. The spectrum will be a continuous band of color. If now the air is admitted at the base of the burner, and if a clean platinum wire is held in the flame directly in front of the slit, the white-hot platinum will also give a continuous spectrum.*

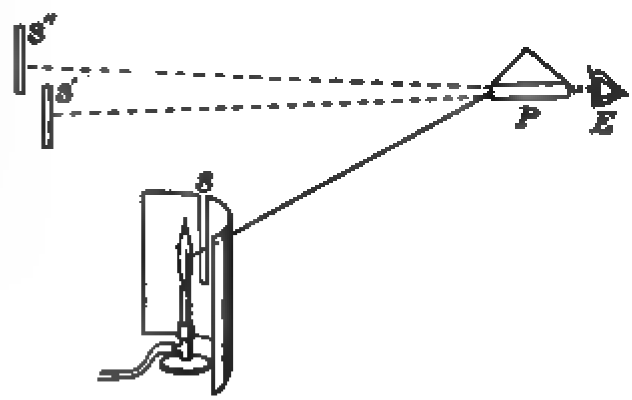


FIG. 447. Arrangement for viewing spectra

All incandescent solids and liquids are found to give spectra of this type which contain all the wave lengths from the extreme red to the extreme violet. The continuous spectrum of a luminous gas flame is due to

*By far the most satisfactory way of performing these experiments with spectra is to provide the class with cheap plate-glass prisms, like those used in Experiment 50 of the authors' Manual, rather than to attempt to project line spectra.

the incandescence of solid particles of carbon suspended in the flame. The presence of these solid particles is proved by the fact that soot is deposited on bodies held in a white flame.

478. Bright-line spectra. Let a bit of asbestos or a platinum wire be dipped into a solution of common salt (sodium chloride) and held in the flame, care being taken that the wire itself is held so low that the spectrum due to it cannot be seen. The continuous spectrum of the preceding paragraph will be replaced by a clearly defined yellow image of the slit which occupies the position of the yellow portion of the spectrum. This shows that the light from the sodium flame is not a compound of a number of wave lengths, but is rather of just the wave length which corresponds to this particular shade of yellow. The light is now coming from the incandescent sodium vapor and not from an incandescent solid, as in the preceding experiments.

Let another platinum wire be dipped in a solution of lithium chloride and held in the flame. Two distinct images of the slit, s' and s'' (Fig. 447), will be seen, one in red and one in yellow. Let calcium chloride be introduced into the flame. One distinct image of the slit will be seen in the green and another in the red. Strontium chloride will give a blue and a red image, etc. (The yellow sodium image will probably be present in each case, because sodium is present as an impurity in nearly all salts.)

These narrow images of the slit in the different colors are called the characteristic *spectral lines* of the substances. The experiments show that incandescent vapors and gases give rise to *bright-line spectra,* and not continuous spectra like those produced by incandescent solids and liquids (see on opposite page). The method of analyzing compound substances through a study of the lines in the spectra of their vapors is called *spectrum analysis.* It was first used by Bunsen in 1859.

479. The solar spectrum. Let a beam of sunlight pass first through a narrow slit S (Fig. 448), not more than $\frac{1}{5}$ millimeter in width, then through a prism P, and finally let it fall on a screen S', as shown in Fig. 448. Let the position of the prism be changed until a beam of white light is reflected from one of its faces to that portion of the screen which was previously occupied by the central portion of the spectrum.

Then let a lens L be placed between the prism and the slit, and moved back and forth until a perfectly sharp white image of the slit is formed on the screen. This adjustment is made in order to get the slit S and the screen S' in the positions of conjugate foci of the lens. Now let the prism be turned to its original position. The spectrum on the screen will then consist of a series of colored images of the slit arranged side by side. This is called a pure spectrum, to distinguish it from the spectrum shown in Fig. 440, in which no lens was used to bring the rays of each particular color to a particular point, and in which there was therefore much overlapping of the different colors. If the slit and screen are exactly at conjugate foci of the lens, and if the slit is sufficiently narrow, the spectrum will be seen to be crossed vertically by certain dark lines.

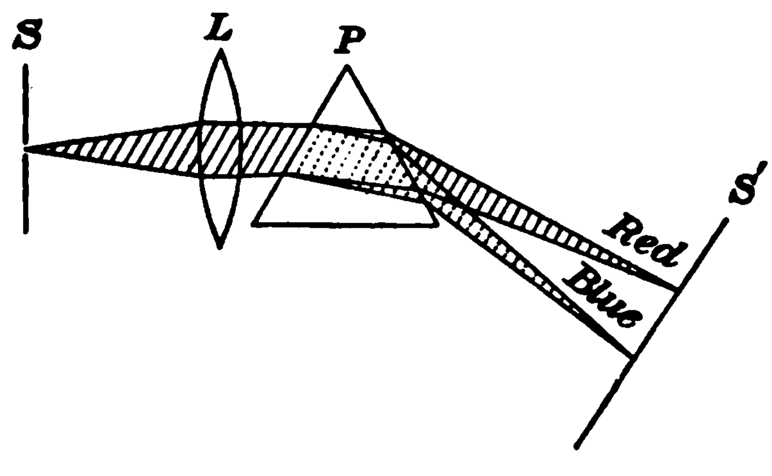


FIG. 448. Arrangement for obtaining a pure spectrum

These lines were first observed by the Englishman Wollaston in 1802, and were first studied carefully by the German Fraunhofer in 1814, who counted and mapped out as many as seven hundred of them. They are called, after him, the *Fraunhofer lines.* Their existence in the solar spectrum shows that certain wave lengths are absent from sunlight, or, if not entirely absent, are at least much weaker than their neighbors. When the experiment is performed as described above, it will usually not be possible to count more than five or six distinct lines.

480. Explanation of the Fraunhofer lines. Let the solar spectrum be projected as in § 479. Let a few small bits of metallic sodium be laid upon a loose wad of asbestos which has been saturated with alcohol. Let the asbestos so prepared be held to the left of the slit, or between the slit and the lens, and there ignited. A black band will at once appear in the yellow portion of the spectrum, in the place where the color is exactly that of the sodium flame itself; or, if the focus was sufficiently sharp so that a dark line could be seen in the yellow before the sodium

was introduced, this line will grow very much blacker when the sodium is burned. Evidently, then, this dark line in the yellow part of the solar spectrum is in some way due to sodium vapor through which the sunlight has somewhere passed.

The experiment at once suggests the explanation of the Fraunhofer lines. The white light which is emitted by the hot nucleus of the sun, and which contained all wave lengths, has had certain wave lengths weakened by absorption as it passed through the vapors and gases surrounding the sun and the earth. For it is found that *every gas or vapor will absorb exactly those wave lengths which it is itself capable of emitting when incandescent.* This is for precisely the same reason that a tuning fork will respond to, that is, absorb, only vibrations which have the same period as those which it is itself able to emit. Since, then, the dark line in the yellow portion of the sun's spectrum is in exactly the same place as the bright yellow line produced by incandescent sodium vapor, or the dark line which is produced whenever white light shines through sodium vapor, we infer that sodium vapor must be contained in the sun's atmosphere. By comparing in this way the positions of the lines in the spectra of different elements with the positions of various dark lines in the sun's spectrum, many of the elements which exist on the earth have been proved to exist also in the sun. For example, Kirchhoff showed that the four hundred sixty bright lines of iron which were known to him were all exactly matched by dark lines in the solar spectrum. Fig. 449 shows a copy of a

Fig. 449. Comparison of solar and iron spectra

photograph of a portion of the solar spectrum in the middle, and the corresponding bright-line spectrum of iron each side of it. It will be seen that the coincidence of bright and dark lines is perfect.

481. Doppler's principle applied to light waves. We have seen (see The Doppler effect, § 387, p. 326) that the effect of the motion of a sounding body toward an observer is to shorten slightly the wave length of the note emitted, and the effect of motion away from an observer is to increase the wave length. Similarly, when a star is moving toward the earth, each particular wave length emitted will be slightly less than the wave length of the corresponding light from a source on the earth's surface. Hence in this star's spectrum all the lines will be displaced slightly toward the violet end of the spectrum. If a star is moving away from the earth, all its lines will be displaced toward the red end. From the direction and amount of displacement, therefore, we can calculate the velocity with which a star is moving toward or receding from the solar system. Observations of this sort have shown that some stars are moving through space toward the solar system with a velocity of 150 miles per second, while others are moving away with almost equal velocities. The whole solar system appears to be sweeping through space with a velocity of about 12 miles per second; but even at this rate it would be at least 70,000 years before the earth would come into the neighborhood of the nearest star, even if it were moving directly toward it.

QUESTIONS AND PROBLEMS

1. From the table on page 403 calculate how many waves of red and of violet light there are to an inch.

2. In what part of the sky will a rainbow appear if it is formed in the early morning?

3. Why do we believe that there is sodium in the sun?

4. What sort of spectrum should moonlight give? (The moon has no atmosphere.)

5. If you were given a mixture of a number of salts, how would you proceed, with a Bunsen burner, a prism, and a slit, to determine whether or not there was any calcium in the mixture?

6. Draw a diagram of a slit, a prism, and a lens, so placed as to form a pure spectrum.

7. How can you show that the wave lengths of red and green lights are different, and how can you determine which one is the longer?

CHAPTER XXI

INVISIBLE RADIATIONS

Radiation from a Hot Body

482. Invisible portions of the spectrum. When a spectrum is photographed, the effect on the photographic plate is found to extend far beyond the limits of the shortest visible violet rays. These so-called *ultra-violet rays* have been photographed and measured at the Ryerson Physical Laboratory, University of Chicago, down to a wave length of .00000273 centimeter, which is only one fifteenth the wave length of the shortest violet waves.

The longest rays visible in the extreme red have a wave length of about .00008 centimeter, but delicate thermoscopes reveal a so-called *infra-red* portion of the spectrum, the investigation of which was carried, in 1912, by Rubens and von Baeyer of Berlin, to wave lengths as long as .03 centimeter, 400 times as long as the longest visible rays.

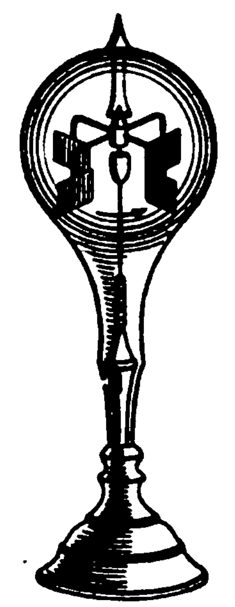


Fig. 450. The Crookes radiometer

The presence of these long heat rays may be detected by means of the radiometer (Fig. 450), an instrument perfected by E. F. Nichols at Dartmouth. In its common form it consists of a partially exhausted bulb, within which is a little aluminium wheel carrying four vanes blackened on one face and polished on the other. When the instrument is held in sunlight or before a lamp, the vanes rotate in such a way that the blackened faces always move away from the source of radiation, because they absorb ether waves better than do the polished faces, and thus become hotter. The heated air in contact with these faces then exerts a greater pressure against them than does the air in contact with the polished faces.

A still simpler way of studying these long heat waves was devised in 1912 by Trowbridge of Princeton. A rubber band AC (Fig. 451) a millimeter wide is stretched to double its length over a glass plate $FGHI$, and the thinnest possible glass staff ED, carrying a light mirror E about 2 millimeters square, is placed under the rubber band at its middle point B. When the spectrum is thrown upon the portion AB of the band, the change in its length produced by the heating causes ED to roll, and a spot of light reflected from E to the wall to shift its position by an amount proportional to the heating.

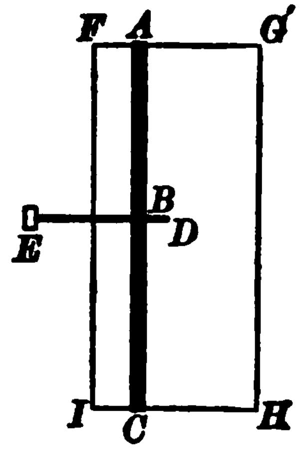


FIG. 451. A simple thermoscope

Let either the radiometer or the thermoscope described above be placed just beyond the red end of the spectrum. It will indicate the presence here of heat rays of even greater energy than those in the visible spectrum. Again, let a red-hot iron ball and one of the detectors be placed at conjugate foci of a large mirror (Fig. 452). The invisible heat rays will be found to be reflected and focused just as are light rays. Next let a flat bottle filled with water be inserted between the detector and any source of heat. It will be found that water, although transparent to light rays, absorbs nearly all of the infra-red rays. But if the water is replaced by carbon bisulphide, the infra-red rays will be freely transmitted, even though the liquid is rendered opaque to light waves by dissolving iodine in it.

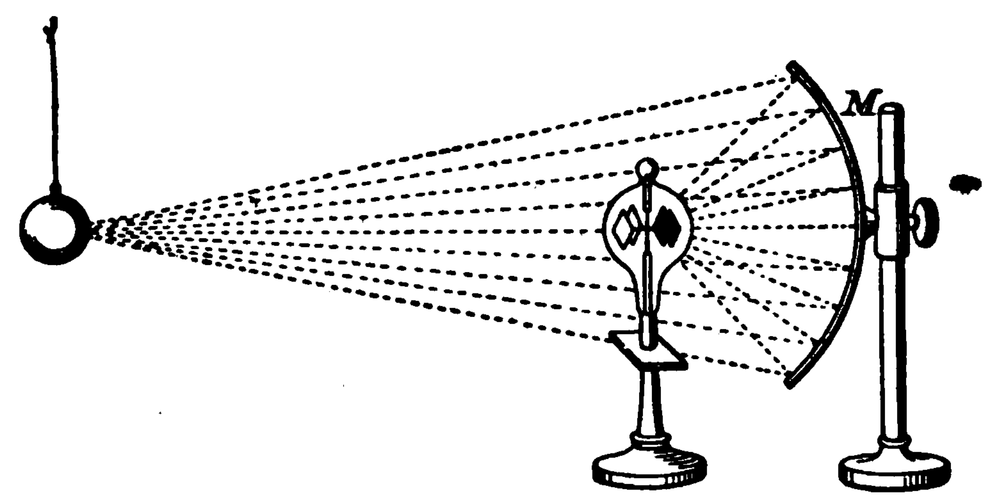


FIG. 452. Reflection of infra-red rays

483. Radiation and temperature. All bodies, even such as are at ordinary temperatures, are continually radiating energy in the form of ether waves. This is proved by the fact that even if a body is placed in the best vacuum obtainable, it continually falls in temperature when surrounded by a colder body, — for example, liquid air. The ether waves emitted at ordinary temperatures are doubtless very long as compared with light waves. As the temperature is raised,

more and more of these long waves are emitted, but shorter and shorter waves are continually added. At about 525° C. the first visible waves, that is, those of a dull red color, begin to appear. From this temperature on, owing to the addition of shorter and shorter waves, the color changes continuously, — first to orange, then to yellow, and, finally, between 800° C. and 1200° C., to white. In other words, all bodies get "red-hot" at about 525° C. and "white-hot" at from 800° C. to 1200° C.

Some idea of how rapidly the total radiation of ether waves increases with increase of temperature may be obtained from the fact that a hot platinum wire gives out thirty-six times as much light at 1400° C. as it does at 1000° C., although at the latter temperature it is already white-hot. The radiations from a hot body are sometimes classified as heat rays, light rays, and chemical, or actinic, rays. The classification is, however, misleading, since all ether waves are heat waves in the sense that, when absorbed by matter, they produce heating effects, that is, molecular motions. *Radiant heat is, then, the radiated energy of ether waves of any and all wave lengths.*

484. Radiation and absorption. Although all substances begin to emit waves of a given wave length at approximately the same temperature, the total rate of emission of energy at a given temperature varies greatly with the nature of the radiating surface. In general, experiment shows that *surfaces which are good absorbers of ether radiations are also good radiators.* From this it follows that *surfaces which are good reflectors,* like the polished metals, *must be poor radiators.*

Thus, let two sheets of tin, 5 or 10 centimeters square, one brightly polished and the other covered on one side with lampblack, be placed in vertical planes about 10 centimeters apart, the lampblacked side of one facing the polished side of the other. Let a small ball be stuck with a bit of wax to the outer face of each. Then let a hot metal

plate or ball (Fig. 453) be held midway between the two. The wax on the tin with the blackened face will melt and its ball will fall first, showing that the lampblack absorbs the heat rays faster than does the polished tin. Now let two blackened glass bulbs be connected, as in Fig. 454, through a U-tube containing colored water, and let a well-polished tin can, one side of which has been blackened, be filled with boiling water and placed between them. The motion of the water in the U-tube will show that the blackened side of the can is radiating heat much more rapidly than the other, although the two are at the same temperature.

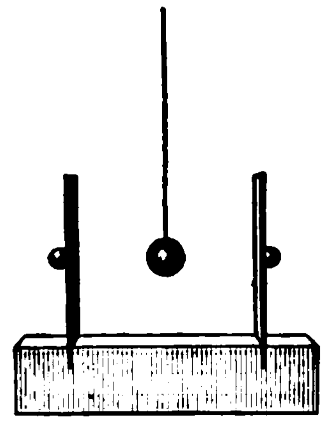


FIG. 453. Good reflectors are poor absorbers

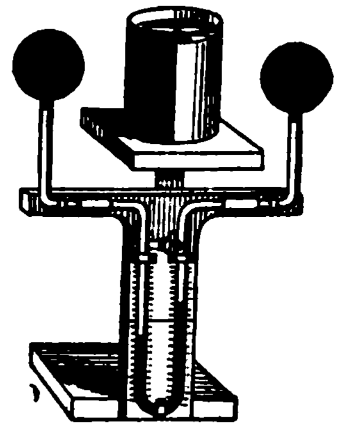


FIG. 454. Good absorbers are good radiators

QUESTIONS AND PROBLEMS

1. The atmosphere is transparent to most of the sun's rays. Why are the upper regions of the atmosphere so much colder than the lower regions?

2. When one is sitting in front of an open-grate fire, does he receive most heat by conduction, by convection, or by radiation?

3. Sunlight in coming to the eye travels a much longer air path at sunrise and sunset than it does at noon. Since the sun appears red or yellow at these times, what rays are absorbed most by the atmosphere?

4. Glass transmits all the visible waves, but does not transmit the long infra-red rays. From this fact explain the principle of the hotbed.

5. Which will be cooler on a hot day, a white hat or a black one?

6. Will tea cool more quickly in a polished or in a tarnished metal vessel?

7. Which emits the more red rays, a white-hot iron or the same iron when it is red-hot?

8. Liquid-air flasks and thermos bottles are double-walled glass vessels with a vacuum between the walls. Liquid air will keep many times longer if the glass walls are silvered than if they are not. Why? Why is the space between the walls evacuated?

Electrical Radiations

485. Proof that the discharge of a Leyden jar is oscillatory. We found in § 408, p. 346, that the sound waves sent out by a sounding tuning fork will set into vibration an adjacent fork, provided the latter has the same natural period as the former. Following is the complete electrical analogy of this experiment.

Let the inner and outer coats of a Leyden jar *A* (see Fig. 455) be connected by a loop of wire *cdef*, the sliding crosspiece *de* being arranged so that the length of the loop may be altered at will. Also let a strip of tin foil be brought over the edge of this jar from the inner coat to within about 1 millimeter of the outer coat at *C*. Let the two coats of an exactly similar jar *B* be connected with the knobs *n* and *n′* by a second similar wire loop of fixed length. Let the two jars be placed side by side with their loops parallel, and let the jar *B* be successively charged and discharged by connecting its coats with a static machine or an induction coil. At each discharge of jar *B* through the knobs *n* and *n′* a spark will appear in the other jar at *C*, provided the crosspiece *de* is so placed that the areas of the two loops are equal. When *de* is slid along so as to make one loop considerably larger or smaller than the other, the spark at *C* will disappear.

Fig. 455. Sympathetic electrical vibrations

The experiment therefore demonstrates that two electrical circuits, like two tuning forks, can be *tuned* so as to respond to each other sympathetically, and that just as the tuning forks will cease to respond as soon as the period of one is slightly altered, so this *electric resonance* disappears when the exact symmetry of the two circuits is destroyed. Since, obviously, this phenomenon of resonance can occur only between systems which have *natural periods* of vibration, the experiment proves that the discharge of a Leyden jar is a vibratory, that is, an

oscillatory, phenomenon. As a matter of fact, when such a spark is viewed in a rapidly revolving mirror, it is actually found to consist of from ten to thirty flashes following each other at equal intervals. Fig. 456 is a photograph of such a spark.

In spite of these oscillations the whole discharge may be made to take place in the incredibly short time of $\frac{1}{10,000,000}$ of a second. This fact, coupled with the extreme brightness of the spark, has made possible the surprising results of so-called *instantaneous electric-spark photography*. The plate opposite page 425 shows the passage of a bullet through a soap bubble. The film was rotated continuously instead of intermittently, as in ordinary moving-picture photography. The illuminating flashes, 5000 per second, were so nearly instantaneous that the outlines are not blurred.

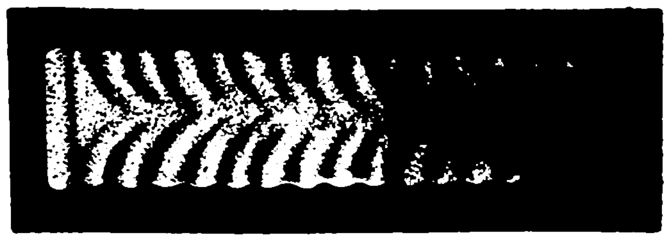


Fig. 456. Oscillations of the electric spark

486. Electric waves. The experiment of § 485 demonstrates not only that the discharge of a Leyden jar is oscillatory but also that these electrical oscillations set up in the surrounding medium disturbances, or waves of some sort, which travel to a neighboring circuit and act upon it precisely as the air waves acted on the second tuning fork in the sound experiment. Whether these are waves in the air, like sound waves, or disturbances in the ether, like light waves, can be determined by measuring their velocity of propagation. The first determination of this velocity was made by Heinrich Hertz (see opposite p. 102) in 1888. He found it to be precisely the same as that of light, that is, 300,000 kilometers per second. *This result shows, therefore, that electrical oscillations set up waves in the ether.* These waves are now known as Hertzian waves.

The length of the waves emitted by the oscillatory spark of instantaneous photography is evidently very great, namely, about $\frac{300,000,000}{10,000,000} = 30$ meters, since the velocity of light is

300,000,000 meters per second, and since there are 10,000,000 oscillations per second; for we have seen in § 382, p. 323, that wave length is equal to velocity divided by the number of oscillations per second. By diminishing the size of the jar and the length of the circuit the length of the waves may be greatly reduced. By causing the electrical discharges to take place between two balls only a fraction of a millimeter in diameter, instead of between the coats of a condenser, electrical waves have been obtained as short as .3 centimeter, only ten times as long as the longest measured heat waves.

487. The coherer. In the experiment of § 485 we detected the presence of the electrical waves by means of a small spark gap *C* in a circuit almost identical with that in which the oscillations were set up. This same means may be employed for the detection of waves many feet away from the source, but the instrument with which electromagnetic waves were first detected hundreds of miles away from the source was *the coherer.* Its principle is illustrated in the following experiment:

Let a glass tube several centimeters long and 6 or 8 millimeters in diameter be filled with fine brass or nickel filings, and let copper wires be thrust into these filings within a distance of about a centimeter of each other. Let these wires be connected in series with a Daniell cell and a simple D'Arsonval galvanometer. The resistance of the loose contacts of the filings will be so great that very little current will flow through the circuit. Now let a static machine be started many feet away. The galvanometer will show a strong deflection as soon as a spark passes between the knobs of the electrical machine. This is because the electric waves, as soon as they fall upon the filings, cause them to cohere, or cling together, so that the electrical resistance of the tube of filings is reduced to a small fraction of what it was before. If the tube is tapped with a pencil, the old resistance will be restored, because the filings have been broken apart by the jar. The experiment may then be repeated.

488. Wireless telegraphy. The last experiment illustrates completely the method of transmitting wireless messages during the first decade after Marconi (see opposite p. 316), in 1896, had realized commercial wireless telegraphy. At present the essential elements of the Marconi

system of wireless telegraphy are as follows: The transmitter consists of an ordinary induction coil or transformer T_1 (Fig. 457,(1)), through the primary of which a current is sent from the alternator A. The secondary S of this transformer charges the condenser C_1 until its potential rises high enough to cause a spark discharge to take place across the gap s. This discharge of C_1 is oscillatory (§ 485), the frequency being of the order of 1,000,000 per second, but subject to the control of

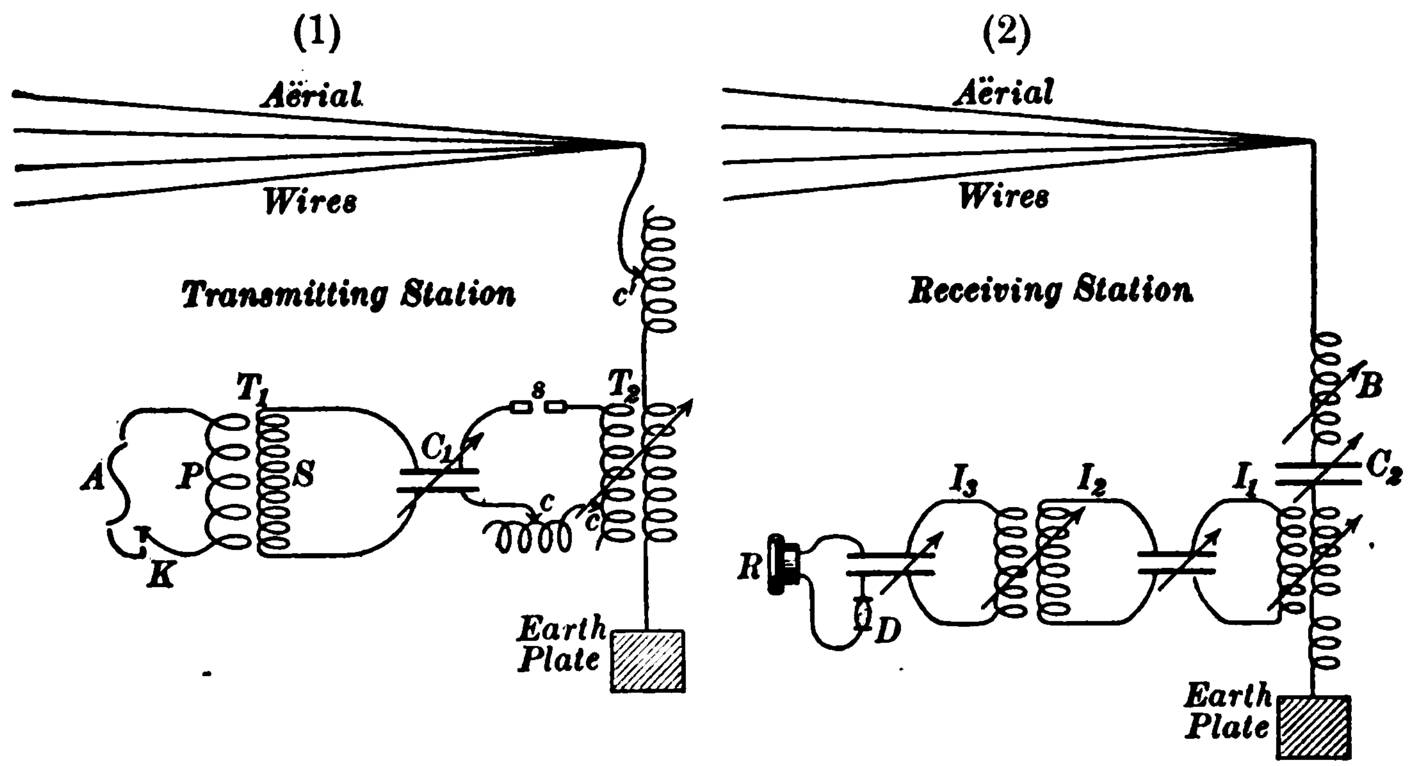


FIG. 457. Transmitting and receiving stations for wireless telegraphy

(1) Transmitting station; (2) receiving station

the operator through the sliding contact c, precisely as in the case illustrated in Fig. 455. The oscillations in this condenser circuit induce oscillations in the aërial-wire system, which is tuned to resonance with it through the sliding contact c'.*

Each spark at s produces one wave train (Fig. 458), which leaves the aërial and moves off through the ether with the velocity of light to the receiving station. Since as high as from 300 to 1000 sparks per second occur at s as long as the key K is kept closed, from 300 to 1000 wave trains pass off one after the other from the aërial every second.

* In the diagram an arrow drawn diagonally across a condenser indicates that, for the sake of tuning, the condenser is made adjustable. Similarly, an arrow across two circuits coupled inductively, like the primary and secondary of the "oscillation transformer" T_2, indicates that the amount of interaction of the two circuits can be varied, as, for example, by sliding one coil a larger or smaller distance inside the other.

THE WIRELESS TELEPHONE UTILIZED IN AVIATION

One of the most notable developments of the war was the directing of a squadron of airplanes in intricate maneuvers by wireless telephone either from the ground or by the commander in the leading plane The upper panel shows the pilot and the observer conversing with special apparatus designed to eliminate plane noises, and the lower panel shows President Wilson talking by wireless to airplanes

Cinematograph Film of a Bullet fired through a Soap Bubble

The flight of the missile may be followed easily. It will be seen that the bubble breaks, not when the bullet enters, but when it emerges. (From "Moving Pictures," by F. A. Talbot. Courtesy of J. B. Lippincott Company)

The waves sent out by this aërial system induce like oscillations in the aërial system of the receiving station (Fig. 457, (2)), it may be thousands of miles away, which is tuned to resonance with it through the variable capacity C_2 and the inductance B. These oscillations induce exactly similar ones in the condenser circuits I_1, I_2, and I_3, all of which are tuned to resonance with the receiving aërial system. The detector of the oscillations in I_3 may be simply a crystal of galena D in series with a telephone receiver R. This crystal, like the tungar rectifier of § 374, has the property of transmitting a current in one direction only.* Were it not for this property the telephone could not be used as a detector, because the frequency is so high, — of the order of a million. In view of this property, however, while the oscillations of a given spark last an intermittent current passes in one direction and then ceases until the oscillations of the next spark arrive. Since from 300 to 1000 of the intermittent wave trains strike upon the receiving aërial each second, the operator at the receiving station hears *a continuous musical sound of the same pitch as long as the key k is depressed*. The working of the key, however, as in ordinary telegraphy, breaks the regular series of wave trains into groups of wave trains, so that the sounds in the receiver (Fig. 459) correspond to the dots and dashes of telegraphy.

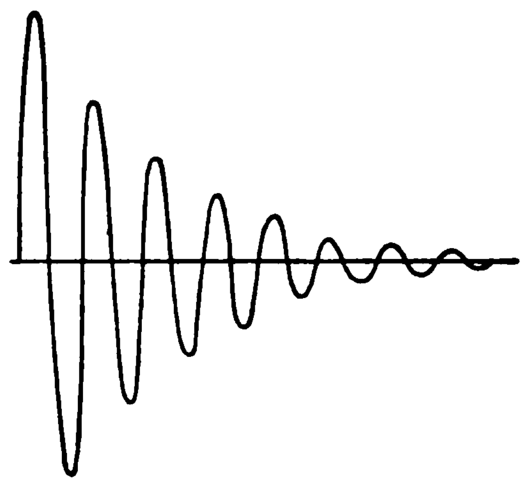


FIG. 458. One wave train from oscillatory discharge

FIG. 459. United States navy standard radio receivers

The stretching of the aërial wires horizontally, instead of vertically as was formerly done, permits to some extent of directive sending and receiving; for, as in the experiment of § 485, the sending and receiving wires work best when they are parallel.

The three-tuned circuits, I_1, I_2, I_3, are used because such a series of tuned circuits does not pick up waves of other periods. For *nonselective*

* Crystal detectors have been largely superseded by the audion detector for both wireless telegraphy and wireless telephony (see opposite pp. 424 and 431).

receiving these circuits are omitted and the detector and telephone are placed directly across the condenser C_2. The resistance of the telephone is so high that it does not interfere with the oscillations of the condenser system across which it is placed.

489. The electromagnetic theory of light. The study of electromagnetic radiations, like those discussed in the preceding paragraphs, has shown not only that they have the speed of light but that they are reflected, refracted, and polarized, — in fact, that they possess all the properties of light waves, the only apparent difference being in their greater wave length. Hence *modern physics regards light as an electromagnetic phenomenon*; that is, light waves are thought to be generated by the oscillations of the electrically charged parts of the atoms. It was as long ago as 1864 that Clerk-Maxwell, (see opposite p. 102), of Cambridge, England, one of the world's most brilliant physicists and mathematicians, showed that it ought to be possible to create ether waves by means of electrical disturbances. But the experimental confirmation of his theory did not come until the time of Hertz's experiments (1888). Maxwell and Hertz together, therefore, share the honor of establishing the modern electromagnetic theory of light.

Cathode and Röntgen Rays

490. The electric spark in partial vacua. Let *a* and *b* (Fig. 460) be the terminals of an induction coil or static machine; *e* and *f*, electrodes sealed into a glass tube 60 or 80 centimeters long; *g*, a rubber tube leading to an air pump by which the tube may be exhausted. Let the coil be started before the exhaustion is begun. A spark will pass between *a* and *b*, since *ab* is a very much shorter path than *ef*. Then let the tube be rapidly exhausted. When the pressure has been reduced to a few centimeters of mercury, the discharge

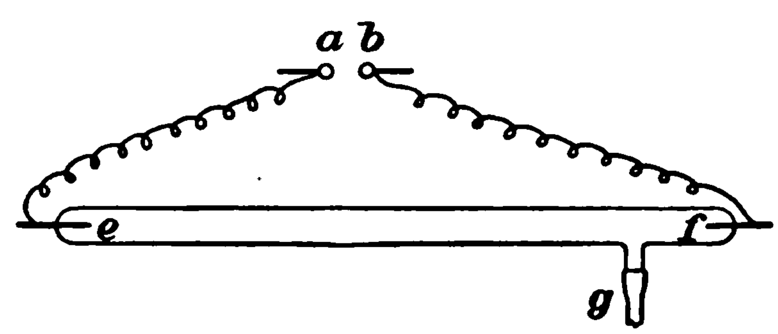


Fig. 460. Discharge in partial vacua

will be seen to choose the long path *ef* in preference to the short path *ab*, thus showing that *an electrical discharge takes place more readily through a partial vacuum than through air at ordinary pressures.*

When the spark first begins to pass between *e* and *f* it will have the appearance of a long ribbon of crimson light. As the pumping is continued this ribbon will spread out until the crimson glow fills the whole tube. Ordinary so-called Geissler tubes are tubes precisely like the above except that they are usually twisted into fantastic shapes and are sometimes surrounded with jackets containing colored liquids, which produce pretty color effects.

491. Cathode rays. When a tube like the above is exhausted to a very high degree, say, to a pressure of about .001 millimeter of mercury, the character of the discharge changes completely. The glow almost entirely disappears from the residual gas in the tube, and certain invisible radiations called *cathode rays* are found to be emitted by the cathode (the terminal of the tube which is connected to the negative terminal of the coil or static machine). These rays manifest themselves, first, by the brilliant fluorescent effects which they produce in the glass walls of the tube, or in other substances within the tube upon which they fall; second, by powerful heating effects; and third, by the sharp shadows which they cast.

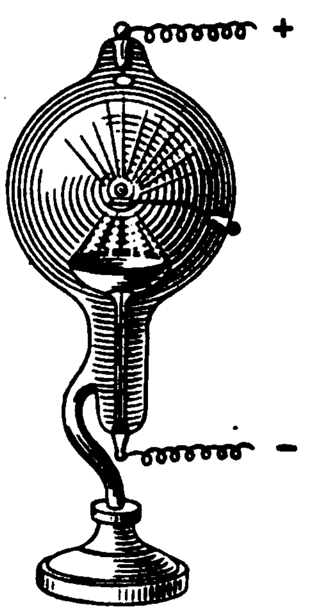


FIG. 461. Heating effect of cathode rays

Thus, if the negative electrode is concave, as in Fig. 461, and a piece of platinum foil is placed at the center of the sphere of which the cathode is a portion, the rays will come to a focus upon a small part of the foil and will heat it white-hot, thus showing that the rays, whatever they are, travel out in straight lines at right angles to the surface of the cathode. This may also be shown nicely by an ordinary bulb of the shape shown in Fig. 463. If the electrode *A* is made the cathode and *B* the anode, a sharp shadow of the piece of platinum

in the middle of the tube will be cast on the wall opposite to *A*, thus showing that the cathode rays, unlike the ordinary electric spark, do not pass between the terminals of the tube, but pass out in a straight line from the cathode surface.

492. Nature of the cathode rays. The nature of the cathode rays was a subject of much dispute between the years 1875, when they first began to be carefully studied, and 1898. Some thought them to be streams of negatively charged particles shot off with great speed from the surface of the cathode, while others thought they were waves in the ether, — some sort of invisible light. The following experiment furnishes very convincing evidence that the first view is correct.

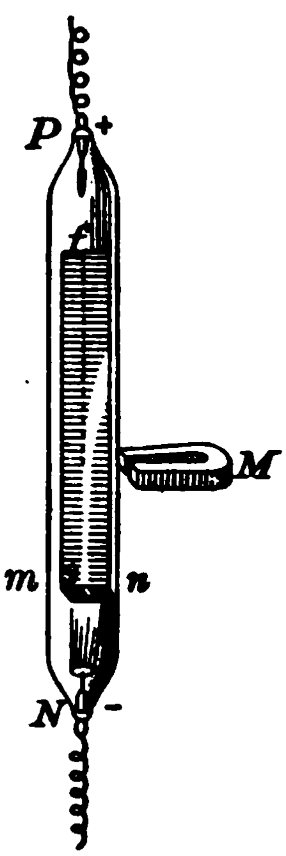


FIG. 462. Deflection of cathode rays by a magnet

NP (Fig. 462) is an exhausted tube within which has been placed a screen *sf* coated with some substance like zinc sulphide, which fluoresces brilliantly when the cathode rays fall upon it; *mn* is a mica strip containing a slit *s*. This mica strip absorbs all the cathode rays which strike it; but those which pass through the slit *s* travel the full length of the tube, and although they are themselves invisible, their path is completely traced out by the fluorescence which they excite upon *sf* as they graze along it. If a magnet *M* is held in the position shown, the cathode rays will be seen to be deflected, and in exactly the direction to be expected if they consisted of negatively charged particles. For we learned in § 298, p. 244, that a moving charge constitutes an electric current, and in § 350, p. 293, that an electric current tends to move in an electric field in the direction given by the motor rule. On the other hand, a magnetic field is not known to exert any influence whatever on the direction of a beam of light or on any other form of ether waves.

When, in 1895, J. J. Thomson (see opposite p. 430), of Cambridge, England, proved that the cathode rays were also deflected by electric charges, as was to be expected if they consist of negatively charged particles, and when Perrin in

Paris had proved that they actually impart negative charges to bodies on which they fall, all opposition to the projected-particle theory was abandoned. The mass and speed of these particles are computed from their deflectibility in magnetic and electric fields.

Cathode rays are then to-day universally recognized as streams of electrons shot off from the surface of the cathode with speeds which may reach the stupendous value of 100,000 miles per second.

493. X rays. It was in 1895 that Röntgen (see opposite p. 436) first discovered that wherever the cathode rays impinge upon the walls of a tube, or upon any obstacles placed inside the tube, they give rise to another type of invisible radiation which is now known under the name of *X rays* or *Röntgen rays.* In the ordinary X-ray tube (Fig. 463) a thick piece of platinum *P* is placed in the center to serve as a target for the cathode rays, which, being emitted at right angles to the concave surface of the cathode *C*, come to a focus at a point on the surface of this plate. This is the point at which the X rays are generated and from which they radiate in all directions. The target *P* is sometimes made of a heavy piece of tungsten.

FIG. 463. An X-ray bulb

In order to convince one's self of the truth of this statement it is only necessary to observe an X-ray tube in action. It will be seen to be divided into two hemispheres by the plane which contains the platinum plate (see Fig. 463). The hemisphere which is facing the source of the X rays will be aglow with a greenish fluorescent light, while the other hemisphere, being screened from the rays, is darker. By moving a fluoroscope (a zinc-sulphide screen) about the tube it will be made evident that the rays which render the bones visible come from *P*.

494. Nature of X rays. While X rays are like cathode rays in producing fluorescence, and also in that neither of them can be refracted or polarized, as light is, they nevertheless differ from cathode rays in several important respects. First, X rays penetrate many substances which are quite impervious to cathode rays; for example, they pass through the walls of the glass tube, while cathode rays ordinarily do not. Again, X rays are not deflected either by a magnet or by an electrostatic charge, nor do they carry electrical charges of any sort. Hence it is certain that they do not consist, like cathode rays, of streams of electrically charged particles.

It has recently been shown that X rays are extremely short waves similar to but very much shorter than light waves, and of a variety of lengths. They are so short that the smoothest mirror we can manufacture is so rough in comparison that it diffuses them. By taking advantage of the regular arrangement of the molecules in the faces of crystals (mica, for example) a kind of reflection known as interference reflection is obtained when the X rays strike at certain favorable angles (see opposite p. 437 for X-ray spectra). Many of the X rays from an ordinary X-ray tube are so short that it would require 250,000,000 of them to make an inch. This represents a rate of vibration of 3,000,000,000,000,000,000 per second.

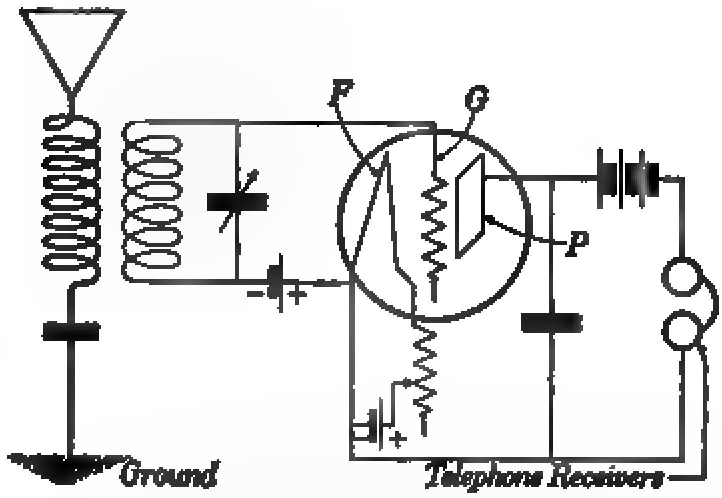
495. X rays render gases conducting. One of the notable properties which X rays possess in common with cathode rays is the property of causing any electrified body on which they fall to slowly lose its charge.

To demonstrate the existence of this property let any X-ray bulb be set in operation within 5 or 10 feet of a charged gold-leaf electroscope. The leaves at once begin to fall together.

The reason for this is that the X rays shake loose electrons from the atoms of the gas and thus fill it with positively and negatively charged particles, each negative particle being at the instant of separation an electron, and each positive particle an

SIR JOSEPH THOMSON (1856–)

Most conspicuous figure in the development of the "physics of the electron"; born in Manchester, England; educated at Cambridge University; Cavendish professor of experimental physics in Cambridge since 1884; author of a number of books, the most important of which is the "Conduction of Electricity through Gases," 1903; author or inspirer of much of the recent work, both experimental and theoretical, which has thrown light upon the connection between electricity and matter; worthy representative of twentieth-century physics



The extraordinary developments in electronics, in which Sir Joseph Thomson has played so important a part, have had commercial consequences, of which the following are perhaps the most significant: In July, 1914, through the development of the DeForest audion into a distortionless telephone relay and amplifier, and the insertion of these amplifiers into suitably chosen places in the telephone line between San Francisco and New York, the research physicists of the Western Electric Company were able to give numerous demonstrations in which audiences in New York and Boston were able to hear with perfect distinctness the splashing of the waves in the San Francisco harbor. By the summer of 1915 the same group of men had succeeded in throwing telephonic speech up into the antennæ of the wireless station at Arlington with such intensity that it traveled without wires a third of the way around the world and was heard so distinctly at receiving stations in both Honolulu and Paris that even the voices of the speakers in Washington could be recognized. The illustration at the left is a cut ($\frac{1}{4}$ size) of one of the tubes with which this extraordinary scientific feat was performed. The simplified circuit of a thermionic amplifier is shown in the diagram above. The enfeebled incoming speech frequencies vary the potential of the grid G, and these variations produce like variations in the electronic currents flowing from the hot filament F to the plate P and thence into the circuit in which the amplified current is needed. By the use of these devices the enormous energy amplifications of 10,000,000,000,000-fold have been obtained

Amplifier, and Diagram of Receiving and Amplifying Set

atom from which an electron has been detached. Any charged body in the gas therefore draws toward itself charges of sign opposite to its own, and thus becomes discharged.

496. X-ray pictures. The most striking property of X rays is their ability to pass through many substances which are wholly opaque to light, — for example, cardboard, wood, leather, and flesh. Thus, if the hand is held close to a photographic plate and then exposed to X rays, a shadow picture of the denser portions of the hand, that is, the bones, is formed upon the plate. Opposite page 359 is shown an X-ray picture of the thorax of a living human being.

RADIOACTIVITY

497. Discovery of radioactivity. In 1896 Henri Becquerel (see opposite p. 436), in Paris, performed the following experiment. He wrapped a photographic plate in a piece of perfectly opaque black paper, laid a coin on top of the paper, and suspended above the coin a small quantity of the mineral uranium. He then set the whole away in a dark room and let it stand for several days. When he developed the photographic plate he found upon it a shadow picture of the coin similar to an X-ray picture. He concluded, therefore, that *uranium possesses the property of spontaneously emitting rays of some sort which have the power of penetrating opaque objects and of affecting photographic plates, just as* X *rays do.* He also found that these rays, which he called *uranium rays*, are like X rays in that they discharge electrically charged bodies on which they fall. He found also that the rays are emitted by all uranium compounds.

498. Radium. It was but a few months after Becquerel's discovery that Madame Curie (see opposite p. 436), in Paris, began an investigation of all the known elements, to find whether any of the rest of them possessed the remarkable

property which had been found to be possessed by uranium. She found that one of the remaining known elements, namely, thorium, the chief constituent of Welsbach mantles, is capable, together with its compounds, of producing the same effect. After this discovery the rays from all this class of substances began to be called *Becquerel rays*, and all substances which emitted such rays were called *radioactive* substances.

But in connection with this investigation Madame Curie noticed that pitchblende, the crude ore from which uranium is extracted, and which consists largely of uranium oxide, would discharge her electroscope about four times as fast as pure uranium. She inferred, therefore, that the radioactivity of pitchblende could not be due solely to the uranium contained in it, and that pitchblende must therefore contain some hitherto unknown element which has the property of emitting Becquerel rays more powerfully than uranium or thorium. After a long and difficult search she succeeded in separating from several tons of pitchblende a few hundredths of a gram of a new element which was capable of discharging an electroscope more than a million times as rapidly as either uranium or thorium. She named this new element *radium.*

499. Nature of Becquerel rays. That these rays which are spontaneously emitted by radioactive substances are not X rays, in spite of their smilarity in affecting a photographic plate, in causing fluorescence, and in discharging electrified bodies, is proved by the fact that they are found to be deflected by both magnetic and electric fields, and by the further fact that they impart electric charges to bodies upon which they fall. These properties constitute strong evidence that *radioactive substances project from themselves electrically charged particles.*

But an experiment performed in 1899 by Rutherford (see opposite p. 436), then of McGill University, Montreal, showed that Becquerel rays are complex, consisting of three different types of radiation, which he named the *alpha*, *beta*, and

gamma rays. The beta rays are found to be identical in all respects with cathode rays; that is, *they are streams of electrons* projected with velocities varying from 60,000 to 180,000 miles per second. The alpha rays are distinguished from these by their very much smaller penetrating power, by their very much greater power of rendering gases conductors, by their very much smaller deflectibility in magnetic and electric fields, and by the fact that *the direction of the deflection is opposite to that of the beta rays.* From this last fact, discovered by Rutherford in 1903, the conclusion is drawn that the alpha rays consist of *positively* charged particles; and from the amount of their deflectibility their mass has been calculated to be about four times that of the hydrogen atom, that is, about 7000 times the mass of the electron, and their velocity to be about 20,000 miles per second. Rutherford and Boltwood have collected the alpha particles in sufficient amount to identify them definitely as *positively charged atoms of helium.*

The difference in the sizes of the alpha and beta particles explains why the latter are so much more penetrating than the former, and why the former are so much more efficient than the latter in knocking electrons out of the molecules of a gas and rendering it conducting. A sheet of aluminium foil .005 centimeter thick cuts off completely the alpha rays but offers practically no obstruction to the passage of the beta and gamma rays.

The gamma rays are very much more penetrating than even the beta rays, and are not at all deflected by magnetic or electric fields. They are regular waves in the ether, like X rays, only shorter; and they are commonly supposed to be produced by the impact of the beta particles on surrounding matter.

500. Crookes's spinthariscope. In 1903 Sir William Crookes (see opposite p. 358) devised a little instrument, called the spinthariscope, which furnishes very direct and striking evidence that particles are being continuously shot off from radium with enormous velocities. In the

spinthariscope a tiny speck of radium *R* (Fig. 464) is placed about a millimeter above a zinc-sulphide screen *S*, and the latter is then viewed through a lens *L*, which gives from ten to twenty diameters magnification. The continuous soft glow of the screen, which is all one sees with the naked eye, is resolved by the lens into hundreds of tiny flashes of light. The appearance is as though the screen were being fiercely bombarded by an incessant rain of projectiles, each impact being marked by a flash of light, just as sparks fly from a flint when struck with steel. The experiment is a very beautiful one, and it furnishes very direct and convincing evidence that radium is continually projecting particles from itself at stupendous speeds. The flashes are due to the impacts of the *alpha*, not the *beta*, particles against the zinc-sulphide screen.

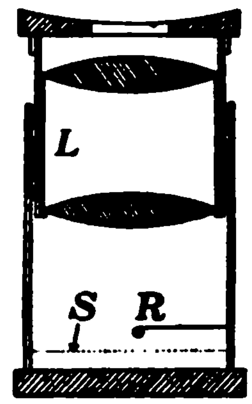


FIG. 464. Crookes's spinthariscope

A mixture composed of a radium compound and zinc sulphide glows constantly and is used for the dials of airplane instruments, compasses, and watches, as well as on gun sights, making them visible for night use.

501. The disintegration of radioactive substances. Whatever be the cause of this ceaseless emission of particles exhibited by radioactive substances, it is certainly not due to any ordinary chemical reactions; for Madame Curie showed, when she discovered the activity of thorium, that the activity of all the radioactive substances is simply proportional to the amount of the active element present, and has nothing whatever to do with the nature of the chemical compound in which the element is found. Furthermore, radioactivity has been found to be independent of all *physical* as well as chemical conditions. The lowest cold or greatest heat does not appear to affect it in the least. Radioactivity, therefore, is as unalterable a property of the atoms of radioactive substances as is weight itself. It is now known that the atoms of radioactive substances are slowly disintegrating into simpler atoms. Uranium and thorium have the heaviest atoms of all the elements. For some unknown reason they seem not infrequently to become

unstable and project off a part of their mass. This projected mass is the alpha particle. What is left of the atom after the explosion is a new substance with chemical properties different from those of the original atom. This new atom is, in general, also unstable and breaks down into something else. This process is repeated over and over again until some stable form of atom is reached. Somewhere in the course of this atomic catastrophe some electrons leave the mass; these are beta rays.

According to this point of view, which is now generally accepted, radium is simply one of the stages in the disintegration of the uranium atom. The atomic weight of uranium is 238.2; that of radium, about 226; that of helium, 4.00. Radium would then be uranium after the latter has lost 3 helium atoms. The further disintegration of radium through four additional transformations has been traced. It has been conjectured that the fifth and final product is lead. If we subtract 8×4.00 from 238.2, we obtain 206.2, which is very close to the accepted value for lead, namely, 207.2. In a similar way six successive stages in the disintegration of the thorium atom (atomic weight, 232.4) have been found, but the final product is unknown.

502. Energy stored up in the atoms of the elements. In 1903 the two Frenchmen, Curie and Labord, made an epoch-making discovery. It was that radium is continually evolving heat at the rate of about one hundred calories per gram per hour. More recent measurements have given one hundred eighteen calories. This result was to have been anticipated from the fact that the particles which are continually flying off from the disintegrating radium atoms subject the whole mass to an incessant internal bombardment which would be expected to raise its temperature. This measurement of the exact amount of heat evolved per hour enables us to estimate how much heat energy is evolved in the disintegration of one

gram of radium. It is about two thousand million calories,—fully three hundred thousand times as much as is evolved in the combustion of one gram of coal. Furthermore, it is not impossible that similar enormous quantities of energy are locked up in the atoms of *all* substances, existing there perhaps in the form of the kinetic energy of rotation of the electrons. The most vitally interesting question which the physics of the future has to face is, Is it possible for man to gain control of any such store of subatomic energy and to use it for his own ends? Such a result does not now seem likely or even possible; and yet the transformations which the study of physics has wrought in the world within a hundred years were once just as incredible as this. In view of what physics has done, is doing, and can yet do for the progress of the world, can anyone be insensible either to its value or to its fascination?

QUESTIONS AND PROBLEMS

1. Why is it necessary to use a rectifying crystal or an audion in series with a telephone receiver to detect electric waves?

2. Explain why an electroscope is discharged when a bit of radium is brought near it.

3. The wave length of the shortest X rays is about .00000001 cm. How many times greater is the wave length of green light?

William Conrad Röntgen,
Munich

Discoverer of X rays

Antoine Henri Becquerel,
Paris

Discoverer of radioactivity

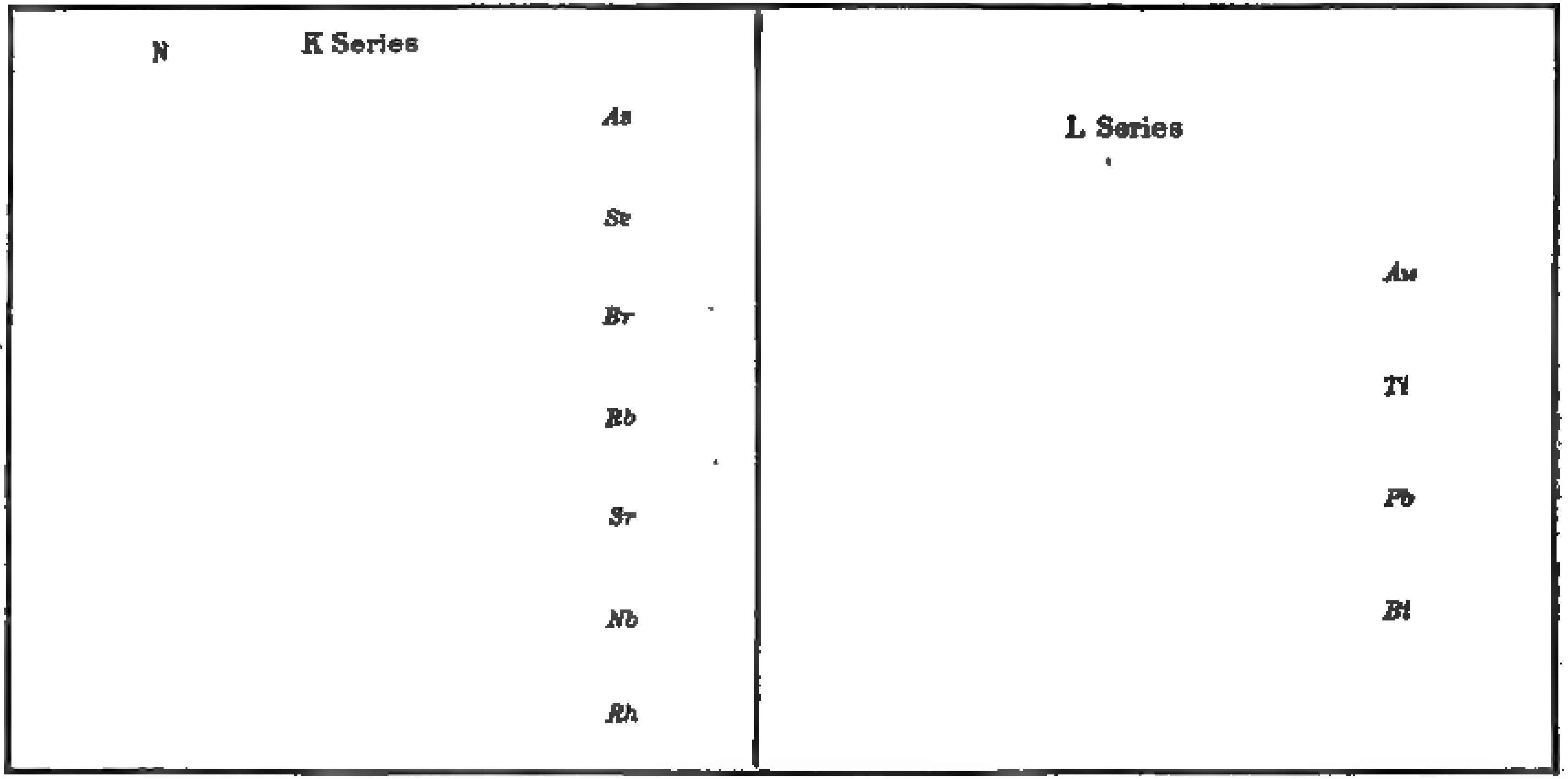
Madame Curie, University
of Paris

Discoverer of radium

E. Rutherford, Cambridge
University (England)

Discoverer of radioactive transformations

A GROUP OF MODERN PHYSICISTS



X-Ray Spectra, photographed by Siegbahn

The photograph illustrates a remarkable discovery made in 1913 in Sir Ernest Rutherford's laboratory by a brilliant young Englishman, Moselev, who at the age of twenty-eight lost his life in the war. Moseley first studied the relations frequencies, of the X-radiations emitted by different substances, and found that the X-ray spectra of all substances were very similar, but that as he went to heavier elements the emitted frequencies progressed in the definite, systematic way shown in the figure. The progression that he found was arithmetical, beginning with hydrogen, the lightest, and going by ninety-two equal steps to uranium, the heaviest. His work is a strong indication that there are but ninety-two elements in nature and that these are all related in some very simple way, all of them probably being built in some way out of hydrogen

APPENDIX

SUPPLEMENTARY QUESTIONS AND PROBLEMS

CHAPTER I. **1.** A new lead pencil is 7 in. long. How many centimeters long is it?

2. From the bed rock upon which the Woolworth Building in New York rests to the top of the tower is 278.3 m. How many feet is it?

3. The wing spread of the NC-4 is 126 ft. How many meters is it?

4. How many kilograms are there in the 16-pound shot?

5. Name three uses made of lead because of its great density, and two uses of cork due to its small density.

6. A flask held 2520 g. of glycerin when filled. What was the capacity of the flask in liters? (See table of densities, p. 9.)

CHAPTER II. **1.** A standpipe 100 ft. high is filled with water. Find the pressure at the bottom in pounds per square foot and in pounds per square inch.

2. Deep-sea fish have been caught in nets at a depth of a mile. How many pounds pressure are there to the square inch at this depth? (Specific gravity of sea water = 1.026.)

3. If the pressure at a tap on the first floor reads 80 lb. per square inch, and at a tap two floors above, 68 lb., what is the difference in feet between the levels of the two taps?

4. Find the total force against the gate of a lock if its width is 60 ft. and the depth of the water 20 ft. Will it have to be made stronger if it holds back a lake than if it holds back a small pond?

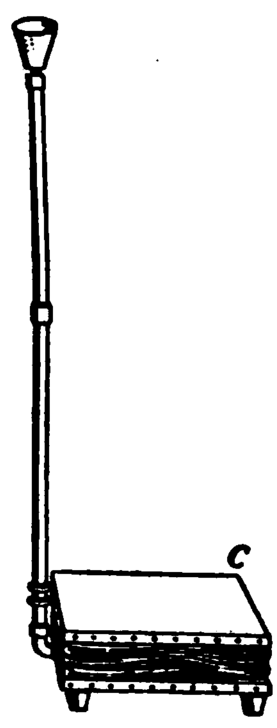


FIG. 465 Hydrostatic bellows

5. Fig. 465 represents an instrument commonly known as the hydrostatic bellows. If the base C is 20 in. square and the tube is filled with water to a depth of 5 ft. above the top of C, what is the value of the weight which the bellows can support?

6. A hydraulic press having a piston 1 in. in diameter exerts a force of 10,000 lb. when 10 lb. are applied to this piston. What is the diameter of the large piston?

7. A floating dock is shown in Fig. 466. When the chambers *c* are filled with water, the dock sinks until the water line is at *A*. The vessel is then floated into the dock. As soon as it is in place, the water is pumped from the chambers until the water line is as low as *B*. Workmen can then get at all parts of the bottom. If each of the chambers is 10 ft. high and 10 ft. wide, what must be the length of the dock if it is to be available for the *Imperator* (Cunard Line), of 50,000 tons' weight?

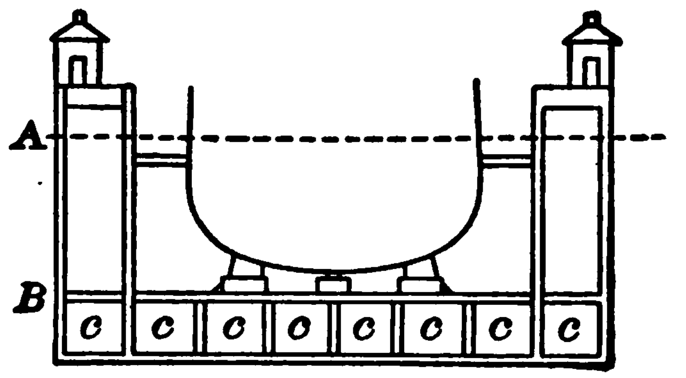


FIG. 466. Floating dock

8. If each boat of a pontoon bridge is 100 ft. long and 75 ft. wide at the water line, how much will it sink when a locomotive weighing 100 tons passes over it?

9. What must be the specific gravity of a liquid in which a body having a specific gravity of 6.8 will float with half its volume submerged?

10. A block of wood 10 in. high sinks 6 in. in water. Find the density of the wood.

11. If this block sank 7 in. in oil, what would be the density of the oil?

12. A graduated glass cylinder contains 190 cc. of water. An egg weighing 40 g. is dropped into the glass; it sinks to the bottom and raises the water to the 225-cc. mark. Find the density of the egg.

CHAPTER III. **1.** Explain the process of making air enter the lungs; of making lemonade rise in a straw.

2. If a circular piece of wet leather having a string attached to the middle is pressed down on a flat, smooth stone, as in Fig. 467, the latter may often be lifted by pulling on the string. Is it pulled up or pushed up? Explain.

3. Make a labeled drawing of a simple Torricellian barometer, naming all the parts in the diagram.

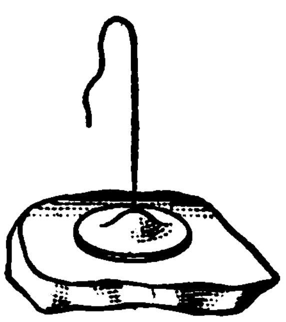


FIG. 467

4. The body of the average man has 15 sq. ft. of surface. What is the total force of the atmosphere upon him? Why is he unconscious of this crushing force?

5. If the variation of the height of a mercury barometer is 2 in., how far did the image rise and fall in Otto von Guericke's water barometer? (See § 42.)

6. What is Boyle's law? A mass of air 3 cc. in volume is introduced into the space above a barometer column which originally stands at 760 mm. The column sinks until it is only 570 mm. high. Find the volume now occupied by the air.

7. There is a pressure of 80 cm. of mercury on 1000 cc. of gas. What pressure must be applied to reduce the volume to 600 cc. if the temperature is kept constant?

8. Pressure tests for boilers or steel tanks of any kind are always made by filling them with water rather than with air. Why?

9. If the water within a diving bell is at a depth of 1033 cm. beneath the surface of a lake, what is the density of the air inside if at the surface the density of air is .0013 and its pressure 76 cm.? What would be the reading of a barometer within the bell?

10. If a diver descends to a depth of 100 ft., what is the pressure to which he is subjected? What is the density of the air in his suit, the density at the surface where the pressure is 75 cm. being .0012? (Assume the temperature to remain unchanged.)

11. How many of the laws of liquids and gases do you find illustrated in the experiment of the Cartesian diver?

12. Pascal proved by an experiment that a siphon would not run if the bend in the arm were more than 34 ft. above the upper water level. He made it run, however, by inclining it sidewise until the bend was less than 34 ft. above this level. Explain.

13. How high will a lift pump raise water if it is located upon the side of a mountain where the barometer reading is 71 cm.?

14. Find the lifting power of a kite balloon whose capacity is 37,000 cu. ft., the lifting power of the gas being 64.4 lb. per 1000 cu. ft. and the weight of the balloon, cordage, car, and observer being 1300 lb.

CHAPTER IV. **1.** Why does a confined body of gas exert pressure inversely proportional to its volume?

2. A lump of copper sulphate placed at the bottom of a graduate filled with water will dissolve and very slowly pass upward, although a copper-sulphate molecule is many times heavier than a water molecule. Explain.

CHAPTER V. **1.** An airplane which flies in still air with a velocity of 120 mi. per hour is flying in a wind whose velocity is 60 mi. per hour toward the east. Find the actual velocity of the airplane and the direction of its motion when headed north; east; south; west.

2. Represent graphically a force of 30 lb. acting southeast and a force of 40 lb. acting southwest at the same point. What will be the magnitude of the resultant, and what will be its approximate direction?

3. Two concurrent forces, each of 50 lb., act at an angle of 60° with each other. Find the resultant graphically.

4. A child weighing 100 lb. sits in a swing. The swing is drawn aside and held in equilibrium by a horizontal force of 40 lb. Find the tension in each of the two ropes of the swing.

5. Four clothes posts were arranged to form a square. A clothes-line was drawn around the outside of the posts with a force of 60 lb. With what force is each post drawn toward the center of the square?

6. A man weighing 150 lb. stood at the middle of a tight-rope whose two parts were each 50 ft. long. What was the tension on the parts of the rope, the weight of the man depressing the center of the rope 1 ft.?

7. A boy pulls a loaded sled weighing 200 lb. up a hill which rises 1 ft. in 5 measured along the slope. Neglecting friction, how much force must he exert?

8. A cask weighing 100 lb. is held at rest upon an inclined plank 8 ft. long and 3 ft. high. By the resolution-and-proportion method find the component of its weight that tends to break the plank.

9. What force will be required to support a 50-lb. ball on an inclined plane of which the length is 10 times the height?

10. A boy is able to exert a force of 75 lb. Neglecting friction, how long an inclined plane must he have in order to push a truck weighing 350 lb. up to a doorway 3 ft. above the ground?

11. Could a kite be flown from an automobile when there is no wind? Explain.

12. Why is it unsafe to stand up in a canoe?

13. If a lead pencil is balanced on its point on the finger, it will be in unstable equilibrium, but if two knives are stuck into it, as in Fig. 468, it will be in stable equilibrium. Why?

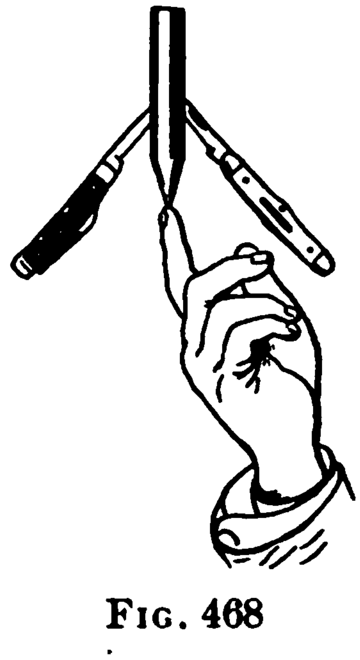


Fig. 468

14. Why does a man lean forward when he climbs a hill?

15. A boy dropped a stone from a bridge and noticed that it struck the water in just 3 sec. How fast was it going when it struck? How high was the bridge above the water?

16. If a body sliding without friction down an inclined plane moves 40 cm. during the first second of its descent, and if the plane is 500 cm. long and 40.8 cm. high, what is the value of g? (Remember that the acceleration down the incline is simply the component (§ 80) of g parallel to the incline.)

17. A ball shot straight upward near a pond was seen to strike the water in 10 sec. How high did it rise? What was its initial speed?

18. A trolley car moving from rest with uniform acceleration acquired a velocity of 10 mi. per nour in 15 sec. What was the acceleration and the distance traversed?

19. A bombing airplane is flying 60 mi. per hour in still air at a height of 1600 ft. In order to score a "bull's-eye," at what distance in advance of the target must the bomb be let go?

20. A rifle weighing 5 lb. discharges a 1-oz. bullet with a velocity of 1000 ft. per second. What will be the velocity of the rifle in the opposite direction?

21. A steamboat weighing 20,000 metric tons is being pulled by a tug which exerts a pull of 2 metric tons. (A metric ton is equal to 1000 kg.) If the friction of the water were negligible, what velocity would the boat acquire in 4 min.? (Reduce mass to grams, force to dynes, and remember that $F = mv/t$.)

22. If a train of cars weighs 200 metric tons, and the engine in pulling 5 sec. imparts to it a velocity of 2 m. per second, what is the pull of the engine in metric tons?

CHAPTER VI. **1.** What must be the cross section of a wire of copper if it is to have the same tensile strength (that is, break with the same weight) as a wire of iron 1 sq. mm. in cross section? (See §107.)

2. How many times greater must the diameter of one wire be than that of another of the same material if it is to have five times the tensile strength?

3. If the position of the pointer on a spring balance is marked when no load is on the spring, and again when the spring is stretched with a load of 10 g., and if the space between the two marks is then divided into ten equal parts, will each of these parts represent a gram? Why?

4. A wire which is twice as thick as another of similar material will support how many times as much weight?

5. A force of 3 lb. stretches 1 mm. a wire that is 1 m. long and .1 mm. in diameter. How much force will it take to stretch 5 mm. a wire of the same material 4 m. long and .2 mm. in diameter?

6. Why does a small stream of water break up into drops instead of falling as a continuous thread?

7. Give four common illustrations of capillary attraction.

8. Explain the watering of flowers by setting the pot in a shallow basin of water.

9. Why does a new and oily steel pen not write well? Why is it difficult to write on oiled paper?

10. Would mercury ascend a lamp wick as oil and water do?

11. Why do some liquids rise while others are depressed in capillary tubes?

12. If water will rise 32 cm. in a tube .1 mm. in diameter, how high will it rise in a tube .01 mm. in diameter?

13. How can you tell whether bubbles which rise from the bottom of a vessel which is being heated are bubbles of air or bubbles of steam?

CHAPTER VII. **1.** A woman in sweeping a rug moved the nozzle of a vacuum sweeper a total distance of 130 ft., using an average force of one-half pound. How much work did she do?

2. Analyze several types of manual labor and see if the definition ($W = Fs$) holds for each. Is not $F \times s$ the thing *paid for* in every case?

3. Explain the use of the rider in weighing (see Fig. 22).

4. Two boys are carrying a bag of walnuts at the middle of a long stick. Will it make any difference whether they walk close to the bag or farther away, so long as each is at the same distance?

5. If 3 horses are to pull equally on a load, how should the whippletree be designed?

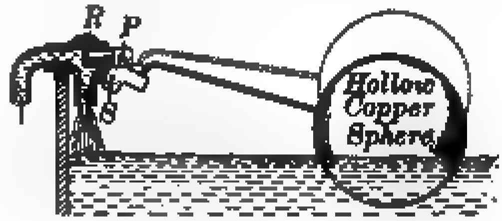


FIG. 469. The automatic float valve

6. Why is it that a couple cannot be balanced by a single force?

7. If the ball of the float valve (Fig. 469) has a diameter of 10 cm., and if the distance from the center of the ball to the pivot S is 20 times the distance from S to the pin P, with what force is the valve R held shut when the ball is half immersed? Neglect weight of ball.

(1) (2)

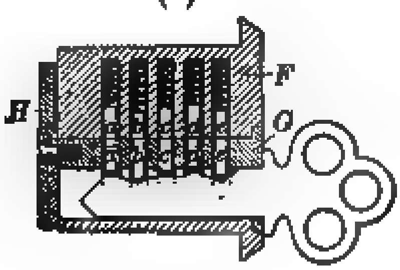


FIG. 470. Yale lock

(1), the right key; (2), the wrong key

8. In the Yale lock (Fig. 470) the cylinder G rotates inside the fixed cylinder F and works the bolt through the arm H. The *right* key raises the pins a', b', c', d', e' until their tops are just even with the top of G. What mechanical principles do you find involved in this device?

9. A lever is 8 ft. long. Where must the fulcrum be placed so that a weight of 300 lb. at one end shall be balanced by 50 lb. at the other?

10. Two horses of unequal strength must be hitched as a team. The one is to pull 360 lb., while the other pulls 288 lb. In a doubletree 50 in. long, where must the pin be placed to permit an even pull?

11. In the differential wheel and axle (Fig. 471) the rope is wound in opposite directions on two axles of different diameter. For a complete revolution of the axle the weight is lifted by a distance equal to one half the difference between the circumferences of the two axles. If the crank has a radius of 2 ft., the larger axle a diameter of 6 in., and the smaller one a diameter of 4 in., find the mechanical advantage of the arrangement. (See differential pulley, p. 119.)

FIG. 471. Differential windlass

12. With the aid of Fig 472 describe the process of winding and setting a watch. The rocker R is pivoted at S; C carries the mainspring and E the hands; $S.P.$ is a light spring which normally keeps the wheel A in mesh with C. Pressing down on P, however, releases A from C and engages B with D. What mechanical principles do you find involved? What happens when M is turned backward?

13. A 150-lb. man runs up a flight of stairs 60 ft. high in 10 sec. What is his horse power while doing it? How do you account for the result?

14. A thousand-barrel tank at a mean elevation of 50 ft. is to be filled with water. How much work must be done to fill it, assuming a barrel of water to weigh 260 lb.? How long would it take a 2-horse-power electric motor to fill it?

FIG. 472. Winding and setting mechanism of a stem-winding watch

15. What must be the horse power of an engine which is to pump 10,000 l. of water per second from a mine 150 m. deep? (Take 76 kilogram meters per second = 1 horse power.)

16. A water motor discharges 100 l. of water per minute when fed from a reservoir in which the water surface stands 50 m. above the level

of the motor. If all of the potential energy of the water were transformed into work in the motor, what would be the horse power of the motor? (The potential energy of the water is the amount of work which would be required to carry it back to the top of the reservoir.)

17. A rifle weighing 8.5 lb. discharges a bullet weighing 0.4 oz. with a velocity of 2600 ft. per second. What is the kinetic energy of the bullet; the velocity of recoil of the rifle; the kinetic energy of the rifle?

CHAPTER VIII. **1.** What fractional part of the air in a room passes out when the air in it is heated from −15° C. to 20° C.? (−15° C. = 258° A.; 20° C. = 293° A.)

2. If the volume of a body of gas at 20° C. and 76 cm. pressure is 500 cc., what is its volume at 50° C. and 70 cm. pressure?

3. An automobile tire contained air under a pressure of 70 lb. per square inch at a temperature of 20° C. On being driven, the temperature of the air rose to 35° C. What was the increase in pressure within the tire?

4. Find the density of the air in a furnace whose temperature is 1000° C., the density at 0° C. being .001293.

5. When the barometric height is 76 cm. and the temperature 0° C., the density of air is .001293. Find the density of air when the temperature is 38° C. and the barometric height is 73 cm. Find the density of air when the temperature is − 40° C. and the barometric height 74 cm.

6. If an iron steam pipe is 60 ft. long at 0° C., what is its length when steam passes through it at 100° C.?

7. If iron rails are 30 ft. long, and if the variation of temperature throughout the year is 50° C., what space must be left between their ends?

8. If the total length of the iron rods *b*, *d*, *e*, and *i* in a compensated pendulum (Fig. 151) is 2 m., what must be the total length of the copper rods *c* if the period of the pendulum is independent of temperature?

9. Two metal bars, one aluminium and the other steel, are both 100 cm. long at 0° C. How much will they differ in length at 30° C.? (See table on page 140.)

CHAPTER IX. **1.** Name three uses and three disadvantages of friction.

2. There is a Pelton wheel at the Sutro tunnel in Nevada which is driven by water supplied from a reservoir 2100 ft. above the level of the motor. The diameter of the nozzle is about $\frac{1}{2}$ in., and that of the wheel but 3 ft., yet 100 H.P. is developed. If the efficiency is 80%, how many cubic feet of water are discharged per second?

3. A turbine having an efficiency of 80% was supplied with 200 cu. ft. of water per second at a head of 50 ft. What horse power was developed?

4. How many calories of heat are generated by the impact of a 200-kilo bowlder when it falls vertically through 100 m.? (The mechanical equivalent of heat = 427 g.m.)

5. Thousands of meteorites are falling into the sun with enormous velocities every minute. From a consideration of the preceding example account for a portion, at least, of the sun's heat.

6. The kinetic energy of mass motion of an automobile running 20 mi. per hour was 37,344 ft. lb. In stopping this car how many B.T.U. were developed in the brakes?

7. 400 g. of aluminium at 100° C. were dropped into 500 g. of water at 20° C. The water equivalent of the calorimeter was 40 grams. Find the resultant temperature. (See table on page 160.)

8. A copper ball weighing 3 kg. was heated to a temperature of 100° C. When placed in water at 15° C. it raised the temperature to 25° C. How many grams of water were there? (See table on page 160.)

9. 100 g. of water at 80° C. are thoroughly mixed with 500 g. of mercury at 0° C. What is the temperature of the mixture?

10. A piece of platinum weighing 10 g. is taken from a furnace and plunged instantly into 40 g. of water at 10° C. The temperature of the water rises to 24° C. What was the temperature of the furnace?

11. How many grams of ice-cold water must be poured into a tumbler weighing 300 g. to cool it from 60° C. to 20° C., the specific heat of glass being .2?

12. If you put a 20-g. silver spoon at 20° C. into a 150-cc. cup of tea at 70° C., how much do you cool the tea?

13. Which would be heated more, a lead or a steel bullet, if they were fired against a target with equal speeds?

14. If the specific heat of lead is .031 and the mechanical equivalent of a calorie 427 g. m., through how many degrees centigrade will a 1000-g. lead ball be raised if it falls from a height of 100 m., provided all of the heat developed by the impact goes into the lead?

15. A car weighing 60,000 kilos slides down a grade which is 2 m. lower at the bottom than at the top and is brought to rest at the bottom by the brakes. How many calories of heat are developed by the friction?

16. Explain why the cylinder of an automobile-tire pump becomes hot when the pump is being used. Why is the air cooled as it escapes from the valve of an automobile tire?

CHAPTER X. **1.** What is the temperature of a mixture of ice and water? What determines whether it is freezing or melting?

2. Why does ice cream seem so much colder to the teeth than ice water?

3. If water were like gold in contracting on solidification, what would happen to lakes and rivers during a cold winter?

4. Equal weights of hot water and ice are mixed, and the result is water at 0° C. What was the temperature of the hot water?

5. Which is the more effective as a cooling agent, 100 lb. of ice at 0° C. or 100 lb. of water at the same temperature? Why?

6. What temperature will result from mixing 10 g. of ice at 0° C. with 200 g. of water at 25° C.?

7. From what height must a gram of ice at 0° C. fall in order to melt itself by the heat generated in the impact?

8. If dry air were placed in a closed vessel when the barometer was 76 cm., and if a dish of water were then introduced within the closed space, what pressure would finally be attained within the vessel if the temperature were kept at 18° C.?

9. If there were moisture on the face, would fanning produce any feeling of coolness in a saturated atmosphere?

10. Would fanning produce any feeling of coolness if there were no moisture on the face?

11. Explain the formation of frost on the window panes in winter.

12. In the fall we expect frost on clear nights when the dew point is low, but not on cloudy nights when the dew point is high. Can you see any reason why a large deposit of dew should prevent the temperature of the air from falling very low?

13. Why does the distillation of a mixture of alcohol and water always result to some extent in a mixture of alcohol and water?

14. How much heat is given up by 30 g. of steam at 100° C. in condensing to water at the same temperature?

15. A vessel contains 300 g. of water at 0° C. and 130 g. of ice. If 25 g. of steam are condensed in it, what will be the resulting temperature?

16. To convert 1 g. of water at 0° C. into steam at 100° C. requires 636 calories. When the boiling point of water is 100° C., how many of these calories are used to vaporize the water? At an elevation where water boils at 90° C., how many calories are required for the vaporization? (Specific heat of steam = 0.5.)

17. Bearing in mind that the cooler the water the less the kinetic agitation of its molecules, why should you expect a larger result at 90° C. than 536 calories?

18. When the steam gauge of a locomotive records 250 lb. per square inch, the steam is at a temperature of 406° F. Explain how the steam produces this great pressure.

19. If the average pressure in the cylinder of a steam engine is 10 kilos to the square centimeter, and the area of the piston is 427 sq. cm.,

how much work is done by the piston in a stroke of length 50 cm.? How many calories did the steam lose in this operation?

20. The total efficiency of a certain 600-horse-power locomotive is 6%; 8000 calories of heat are produced by the burning of 1 g. of the best anthracite coal; how many kilos of such coal are consumed per hour by this engine? (Take 1 H.P. = 746 watts and 1 calorie per second = 4.2 watts.)

CHAPTER XI. **1.** Why are the pipes that carry steam from the boiler to the radiators often covered with cellular asbestos? Why is the cellular structure an advantage?

2. Explain the cause of the sea breeze which occurs in coast regions on summer afternoons.

3. Is the draft through the fire of a kitchen range pushed through or drawn through? Explain.

4. Why should steam radiators be installed on the cold side of a room, for example, near outside walls or windows?

5. Describe all the processes involved in the transference of heat energy from the fire under the steam boiler in a cellar to the rooms containing the radiators.

CHAPTER XII. **1.** If a bar magnet is floated on a piece of cork, will it tend to float toward the north? Why?

2. The dipping needle is suspended from one arm of a steel-free balance and carefully weighed. It is then magnetized. Will its apparent weight increase?

3. When a piece of soft iron is made a temporary magnet by bringing it near the N pole of a bar magnet, will the end of the iron nearest the magnet be an N or an S pole?

4. To which do isogonic lines as a rule correspond most nearly, the parallels or the meridians?

5. Lines connecting those places on the earth where the inclination of the dipping needle is the same are called *isoclinic* lines. Do isoclinic lines in general trend approximately N and S or E and W?

6. With what force will an N magnetic pole of strength 6 attract, at a distance of 5 cm., an S pole of strength 1? of strength 9?

CHAPTER XIII. **1.** Why is repulsion between an unknown body and an electrified pith ball a surer sign that the unknown body is electrified than is attraction?

2. If you charge an electroscope and then bring your hand toward the knob (not touching it), the leaves go closer together. Why?

3. Two small spheres are charged with $+16$ and -4 units of electricity. With what force will they attract each other when at a distance of 4 cm.?

4. If the two spheres of the previous problem are made to touch and are then returned to their former positions, with what force will they act on each other? Will this force be attraction or repulsion?

5. Why is the capacity of a conductor greater when another conductor connected to the earth is near it than when it stands alone?

6. A Leyden jar is placed on a glass plate and 10 units of electricity placed on the inner coating. The knob is then connected to a gold-leaf electroscope. Will the leaves of the electroscope stand farther apart now or after the outside coating has been connected to the earth?

CHAPTER XIV. **1.** Why would an electromagnet made by winding bare wire on a bare iron core be worthless as a magnet?

2. The plane of a suspended loop of wire is east and west. A current is sent through it, passing from east to west on the upper side. What will happen to the loop if it is perfectly free to turn?

3. When a strong current is sent through a suspended-coil galvanometer, what position will the coil assume?

4. If the earth's magnetism is due to a surface charge rotating with the earth, must this charge be positive or negative in order to produce the sort of magnetic poles which the earth has? (This is actually the present theory of the earth's magnetism.)

5. Why must a galvanometer which is to be used for measuring voltages have a high resistance?

6. Why is the E.M.F. of a cell equal to the P.D. of its terminals when on open circuit? (Explain by reference to the water analogy of § 318.)

7. Can you prove from a consideration of Ohm's law that when wires of different resistances are inserted in series in a circuit, the P.D.'s between the ends of the various wires are proportional to the resistances of these wires?

8. How long a piece of No. 30 copper wire will have the same resistance as a meter of No. 30 German-silver wire? (See table of specific resistances, p. 262.)

9. The diameter of No. 20 wire is 31.96 mils (1 mil = .001 in.) and that of No. 30 wire 10.025 mils. Compare the resistances of equal lengths of No. 20 and No. 30 German-silver wires.

10. What length of No. 30 copper wire will have the same resistance as 20 ft. of No. 20 copper wire?

11. What length of No. 20 German-silver wire will have the same resistance as 100 ft. of No. 30 copper wire?

12. A galvanometer has a resistance of 588 ohms. If only one fiftieth of the current in the main circuit is to be allowed to pass through the moving coil, what must be the resistance of the shunt?

13. Ten pieces of wire, each having a resistance of 5 ohms, are connected in parallel (see Fig. 278). If the junction *a* is connected to one terminal of a Daniell cell and *b* to the other, what is the total current which will flow through the circuit when the E.M.F. of the cell is 1 volt and its resistance 2 ohms?

14. If a certain Daniell cell has an internal resistance of 2 ohms and an E.M.F. of 1.08 volts, what current will it send through an ammeter whose resistance is negligible? What current will it send through a copper wire of 2 ohms resistance? through a German-silver wire of 100 ohms resistance?

15. A Daniell cell indicates a certain current when connected to a galvanometer of negligible resistance. When a piece of No. 20 German-silver wire is inserted into the circuit, it is found to require a length of 5 ft. to reduce the current to one half its former value. Find the resistance of the cell in ohms, No. 20 German-silver wire having a resistance of 190.2 ohms per 1000 ft.

16. A coil of unknown resistance is inserted in series with a considerable length of No. 30 German-silver wire and joined to a Daniell cell. When the terminals of a high-resistance galvanometer are touched to the wire at points 10 ft. apart, the deflection is found to be the same as when they are touched across the terminals of the unknown resistance. What is the resistance of the unknown coil? (See § 316, p. 263.)

17. How do we calculate the power consumed in any part of an electric circuit? What horse power is required to run an incandescent lamp carrying .5 ampere at 110 volts?

18. An electric soldering iron allows 5 amperes to flow through it when connected to an E.M.F. of 110 volts. What will it cost, at 12 cents per kilowatt hour, to operate the iron 6 hr. per day for 5 da.?

19. An electric motor developed 2 horse power when taking 16.5 amperes at 110 volts. Find the efficiency of the motor. (One horse power = 746 watts.)

CHAPTER XV. **1.** If the coil of a sensitive galvanometer is set to swinging while the circuit through the coil is open, it will continue to swing for a long time; but if the coil is short-circuited, it will come to rest after a very few oscillations. Why? (The experiment may easily be tried. Remember that currents are induced in the moving coil. Apply Lenz's law.)

2. Show that if the reverse of Lenz's law were true, a motor once started would run of itself and do work; that is, it would furnish a case of perpetual motion.

3. If a series-wound dynamo is running at a constant speed, what effect will be produced on the strength of the field magnets by diminishing the external resistance and thus increasing the current? What will be the effect on the E. M. F.? (Remember that the whole current goes around the field magnets.) (See § 357.)

4. If a shunt-wound dynamo is run at constant speed, what effect will be produced on the strength of the field magnets by reducing the external resistance? What effect will this have on the E. M. F.?

5. In an incandescent-lighting system the lamps are connected in parallel across the mains. Every lamp which is turned on, then, diminishes the external resistance. Explain from a consideration of Problems 3 and 4 why a compound-wound dynamo (Fig. 318) keeps the P. D. between the mains constant.

6. When an electric fan is first started, the current through it is much greater than it is after the fan has attained its normal speed. Why?

7. If the pressure applied at the terminals of a motor is 500 volts, and the back pressure, when running at full speed, is 450 volts, what is the current flowing through the armature, its resistance being 10 ohms?

8. Two successive coils on the armature of a multipolar alternator are cutting lines of force which run in opposite directions. How does it happen that the currents generated flow through the wires in the same direction? (Fig. 310.)

9. A multipolar alternator has 20 poles and rotates 200 times per minute. How many alternations per second will be produced in the circuit?

10. With the aid of the dynamo rule explain why, in Figs. 313 and 315, the current in the conductors under the north poles is moving toward the observer and that in the conductors under the south poles away from the observer.

CHAPTER XVI. **1.** A bullet fired from a rifle with a speed of 1200 ft. per second is heard to strike the target 6 sec. afterwards. What is the distance to the target, the temperature of the air being 20° C.? (Let $x =$ the distance to the target.)

2. A church bell is ringing at a distance of $\frac{1}{2}$ mi. from one man and $\frac{1}{4}$ mi. from another. How much louder would it appear to the second man than to the first if no reflections of the sound took place?

3. A stone is dropped into a well 200 m. deep. At 20° C. how much time will elapse before the sound of the splash is heard at the top?

4. As a circular saw cuts into a block of wood the pitch of the note given out falls rapidly. Why?

5. A clapper strikes a bell once every two seconds. How far from the bell must a man be in order that the clapper may appear to hit the bell at the exact instant at which each stroke is heard?

6. The note from a piano string which makes 300 vibrations per second passes from indoors, where the temperature is 20° C., to outdoors, where it is 0° C. What is the difference in centimeters between the wave lengths indoors and outdoors?

7. A man riding on an express train moving at the rate of 1 mi. per minute hears a bell ringing in a tower in front of him. If the bell makes 280 vibrations per second, how many pulses will strike his ear per second, the velocity of sound being 1120 ft. per second? (The number of extra impulses received per second by the ear is equal to the number of wave lengths contained in the distance traveled per second by the train.) What effect has this upon the pitch? Had he been going from the bell at this rate, how many pulses per second would have reached his ear? How would this affect the pitch?

8. Explain the loud noise that results from singing the right pitch of note into the bunghole of an empty barrel.

9. Why do the echoes which are prominent in empty halls often disappear when the hall is full of people?

CHAPTER XVII. **1.** What is the wave length of middle *C* when the speed of sound is 1152 ft. per second?

2. What is the pitch of a note whose wave length is 5.4 in., the speed being 1152 ft. per second?

3. A wire gives out the note *C* when the tension on it is 4 kg. What tension will be required to give out the note *G*?

4. A wire 50 cm. long gives out 400 vibrations per second. How many vibrations will it give when the length is reduced to 10 cm.? What syllable will represent this note if *do* represents the first note?

5. Two strings, each 6 ft. long, make 256 vibrations per second. If one of the strings is lengthened 1 in., how many beats per second will be heard?

6. If a vibrating string is found to produce the note *C* when stretched by a force of 10 lb., what must be the force exerted to cause it to produce (a) the note *E*? (b) the note *G*?

7. When water is poured into a deep bottle, why does the pitch of the sound rise as the bottle fills?

8. Show what relation exists between the wave lengths of a note and the lengths of the shortest closed and open pipes which will respond to this note.

9. What must be the length of a closed organ pipe which produces the note E? (Take the speed of sound as 340 m. per second.)

10. What is the first overtone which can be produced in an open G organ pipe?

11. What is the first overtone which can be produced by a closed C organ pipe?

CHAPTER XVIII. 1. If the opaque body in Fig. 382 is moved nearer to the screen *ef*, how does the penumbra change?

2. The diameter of the moon is 2000 mi., that of the sun 860,000 mi., and the sun is 93,000,000 mi. away. What is the length of the moon's umbra?

3. If the distance from the center of the earth to the center of the moon were exactly equal to the length of the moon's umbra, over how wide a strip on the earth's surface would the sun be totally eclipsed at any one time?

4. Look at the reflected image of an electric-light filament in a piece of red glass. Why are there two images, one red and one white?

5. Show by a diagram and explanation what is meant by critical angle.

6. The vertical diameter of the sun appears noticeably less than its horizontal diameter just before rising and just before setting because of refraction due to the earth's atmosphere. Explain.

7. In what direction must a fish look in order to see the setting sun? (See Fig. 473.)

FIG. 473. To an eye under water all external objects appear to lie within a cone whose angle is 97°

FIG. 474. Prism glass

8. Fig. 474 represents a section of a plate of prism glass. Explain why glass of this sort is so much more efficient than ordinary window glass in illuminating the rears of dark stores on the ground floor in narrow streets.

9. In which medium, water or air, does light travel the faster? Give reasons for your answer.

10. Does a man above the surface of water appear to a fish below it farther from or nearer to the surface than he actually is? Make an explanatory wave diagram.

11. How far from a screen must a 4-candle-power light be placed to give the same illumination as a 16-candle-power electric light 3 m. away?

12. If two plane surfaces placed 1 m. and 2 m. respectively from a given light receive perpendicularly the same quantity of light, how must their areas compare? State the law involved.

13. If two foot-candles are desired for reading, at what distance from the book must a 32-candle-power lamp be placed?

CHAPTER XIX. **1.** An object 5 cm. long is 50 cm. from a concave mirror of focal length 30 cm. Where is the image, and what is its size?

2. Describe the image formed by a concave lens. Why can it never be larger than the object?

3. What is the focal length of a lens if the image of an object 10 ft. away is 3 ft. from the lens?

4. If the object in Problem 3 is 6 in. long, how long will the image be?

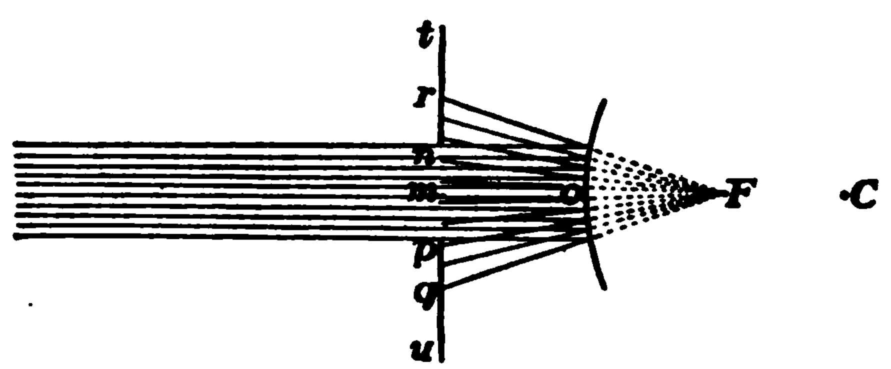


FIG. 475. Determination of focal length of a convex mirror

5. A beam of sunlight falls on a convex mirror through a circular hole in a sheet of cardboard, as in Fig. 475. Prove that when the diameter of the reflected beam *rq* is twice the diameter of the hole *np*, the distance *mo* from the mirror to the screen is equal to the focal length *oF* of the mirror.

6. If a rose *R* is pinned upside down in a brightly illuminated box, a real image may be formed in a glass of water *W* by a concave mirror *C* (Fig. 476). Where must the eye be placed to see the image?

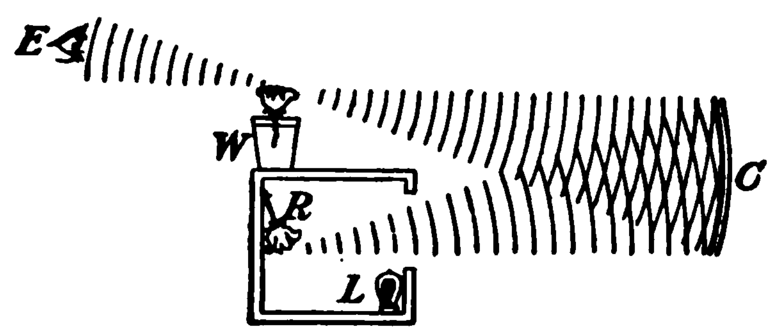


FIG. 476. Image of object at center of curvature

7. How far is the rose from the mirror in the arrangement of Fig. 476?

8. A candle placed 20 cm. in front of a concave mirror has its image formed 50 cm. in front of the mirror. Find the radius of the mirror.

9. The parabolic mirror used as an objective in one of the telescopes at the Mount Wilson observatory is 100 in. in diameter and has a focal length of about 50 ft. What magnification is obtained when it is used with a 2-inch eyepiece; with a 1-inch eyepiece? What is gained by the use of a mirror of such enormous diameter?

10. A compound microscope has a tube length of 8 in., an objective of focal length $\frac{1}{2}$ in., and an eyepiece of focal length 1 in. What is its magnifying power?

11. If the focal length of the eye is 1 in., what is the magnifying power of an opera glass whose objective has a focal length of 4 in.?

12. Explain as well as you can how a telescope forms the image which you see when you look into it.

13. The magnifying power of a microscope is 1000, the tube length is 8 in., and the focal length of the eyepiece is $\frac{1}{2}$ in. What is the focal length of the objective?

CHAPTER XX. 1. If a soap film is illuminated with red, green, and yellow strips of light, side by side, how will the distance between the yellow fringes compare with that between the red fringes? with that between the green fringes? (See table on page 403.)

2. What will be the apparent color of a red body when it is in a room to which only green light is admitted?

3. Will a reddish spot on an oil film be thinner or thicker than an adjacent bluish portion?

4. Explain the ghastly appearance of the face of one who stands under the light of a Cooper-Hewitt mercury-vapor arc lamp.

5. Draw a figure to show how a spectrum is formed by a prism, and indicate the relative positions of the red, the yellow, the green, and the blue in this spectrum.

6. Why is a rainbow never seen during the middle part of the day?

7. If you look at a broad sheet of white paper through a prism, it will appear red at one edge and blue at the other, but white in the middle. Explain why the middle appears uncolored.

8. Can you see any reason why the vibrating molecules of an incandescent gas might be expected to give out a few definite wave lengths, while the particles of an incandescent solid give out all possible wave lengths?

9. Can you see any reason why it is necessary to have the slit narrow and the slit and screen at conjugate foci of the lens in order to show the Fraunhofer lines in the experiment of § 480?

CHAPTER XXI. 1. How are ultra-violet waves detected? What apparatus is used to reveal infra-red waves?

2. Explain how the heat of the sun warms the earth.

3. What is electric resonance? How may it be demonstrated?

4. Describe the construction of an X-ray tube. Describe as well as you can the action within it when in use.

INDEX

Aberration, chromatic, 409
Absolute temperature, 134
Absolute units, 6
Absorption of gases, 102 ff.; of light waves, 414; and radiation, 419
Acceleration, defined, 75; of gravity, 77
Achromatic lens, 410
Adhesion, 92; effects of, 98
Aëronauts, height of ascent of, 37
Air, weight of, 26; pressure of, 27; compressibility of, 34; expansibility of, 34
Air pump, 33, 41
Airplane, frontispiece; principle of gliding of, 78–80; principle of flight of, 80; Vickers-Vimy, 153; Liberty motor in, 191; Wright, 317
Airship, 44
Alternator, 298
Amalgamation of zinc plate, 272
Ammeter, 257
Ampère, portrait of, 256
Ampere, definition of, 251, 257
Ampere turns, 255
Amplifier, 431
Amundsen, 222
Anode, 248
Arc light, 286; automatic feed for, 287
Archimedes, principle of, 21; portrait of, 22
Armature, ring type, 255, 299; drum type, 297, 300, 301, 310
Atmosphere, pressure of, 29; extent and character of, 36; humidity of, 175
Atoms, energy in, 435
Audion, 425, 431
Automobile, 195, 198; clutch and transmission, 196; differential, 197; carburetor, 198, 199; ignition system, 198, 199; anti-glare "lens," 362

Back E. M. F. in motors, 303
Baeyer, von, 417
Balance, 7
Balance wheel, 141
Ball bearings, 145, 146
Balloon, kite, 44, 45; dirigible, 44; helium, 45
Barometer, mercury, 30; von Guericke's, 31; the aneroid, 31; the self-registering, 32, 38
Batteries, primary, 272 ff.; storage, 281, 283
Battleship, 152
Bearings, ball, 145, 146; roller, 146
Beats, 332, 348
Becquerel, 431; portrait of, 436
Bell, Alexander Graham, 316; portrait of, 316
Bell, electric, 259
Bicycle pedal, 146
Binocular vision, 398
Boiler, steam, 191
Boiling points, definition of, 183; effect of pressure on, 183
Boyle's law, stated, 36; explained, 51
British thermal unit, 152
Brittleness, 92
Brooklyn Bridge, 143
Brownian movements, 52
Bunsen, 376

Caisson, 46
Calories, 152; developed by electric currents, 289
Camera, pinhole, 390; photographic, 390
Candle power, of incandescent lamps, 285; of arc lamps, 286; defined, 375
Canner, steam-pressure, 184
Capacity, electric, 240
Capillarity, 96 ff.
Capstan, 117
Carburetor, 198, 199

Cartesian diver, 43
Cathode, defined, 248
Cathode rays, 426
Cells, galvanic, 245; primary, 272 ff.; local action in, 272; theory of, 273; Daniell, 275; Weston, 277; Leclanché, 277; dry, 278; combinations of, 279, 280; storage, 281, 283
Center of gravity, 68
Centrifugal force, 84
Charcoal, absorption by, 102
Charles, law of, 136
Chemical effects of currents, 248
Cigar lighter, platinum-alcohol, 103
Clermont, 135
Clouds, formation of, 174
Clutch, automobile, 196
Coefficient of expansion of gases, 136; of liquids, 138; of solids, 140
Coefficient of friction, 145
Coherer, 423
Cohesion, 92; properties depending on, 92
Coils, magnetic properties of, 252 ff.; currents induced in rotating, 294
Cold storage, 202
Color, and wave length, 402; of bodies, 404; compound, 405; complementary, 406; of pigments, 407; of thin films, 408
Commutator, 298
Compass, 222. *See also* Gyrocompass
Component, 61; magnitude of, 62
Concurrent forces, 60
Condensation of water vapor, 173
Condensers, 240
Conduction, of heat, 203; of electricity, 227
Conjugate foci, 379
Conservation of energy, 155
Convection, 206 ff.
Cooling, of a lake, 139; by expansion, 155; and evaporation, 176; artificial, by solution, 187
Cooper-Hewitt lamp, 288
Coulomb, 251
Couple, 112
Crane, 121
Cream separator, 85
Crilley, 46
Critical angle, 361, 362
Crookes, 358, 433; portrait of, 358
Curie, 431, 432, 434; portrait of, 436
Currents, wind and ocean, 207; electric, defined, 245; effects of electric, 248 ff.; magnetic fields about, 252; measurement of electric, 256 ff.; induced electric, 290 ff.
Curvature, of a liquid surface, 97; of waves, 369; defined, 370; of a mirror, 386; center of, 453

Daniell cell, 275
Davy safety lamp, 205
Declination, 222
Densities, table of, 8, 9
Density, defined, 8; formula for, 9; of air, 26; maximum, of water, 138; of saturated vapor, 171; of electric charge, 234
Descartes, 43
Dew, formation of, 174
Dew point, 175
Dewar flask, 209
Differential, automobile, 197
Diffusion, of gases, 50, 52; of liquids, 54; of solids, 55; of light, 359
Digester, 184
Dipping needle, 223
Discord, 347
Dispersion, 403
Dissociation, 249, 273
Distillation, 185
Diving bell, 45
Diving suit, 46
Doppler effect, in sound, 326; in light, 416
Dry cell, 278
Ductility, 92
Dynamo, principle of, 290; rule for, 293; alternating-current, 296; four-pole direct-current, 300; series-wound, shunt-wound, and compound-wound, 301; defined, 302
Dyne, 86

Eccentric, 191
Echo, 327
Edison, 356; portrait of, 316
Efficiency, defined, 147; of simple machines, 147; of water motors, 148, 149; of steam engines, 193; of electric lights, 285 ff.; of transformers, 312
Elasticity, 90; limits of, 91

Electric charge, unit of, 227; distribution of, 233; density of, 234
Electric iron, 269
Electric motor, principle of, 292; construction of, 301; defined, 302
Electricity, static, 225 ff.; electron theory of, 229, 428 ff.; current of, 244 ff.
Electrolysis of water, 248
Electromagnet, 247, 255
Electromotive force, defined, 263; of galvanic cells, 266; induced, 291; strength of induced, 294; curve of alternating, 297; curve of commutated, 299; back, in motors, 303; in secondary circuit, 307; at make and break, 308
Electron theory, 229, 428 ff.
Electrophorus, 242
Electroplating, 249
Electroscope, 227, 232
Electrostatic voltmeter, 239
Electrotyping, 250
Energy, defined, 122; potential and kinetic, 123; transformations of, 124, 157, 162, 163; formulas for, 125, 126; conservation of, 155; from sun, 157; expenditure of electric, 284; stored in atoms, 435
Engine, steam, 189; steam, defined, 191; compound steam, 193, 298; gas, 191, 194
English equivalent of metric units, 5
Equilibrant, 60
Equilibrium, stable, 69; neutral, 71; unstable, 71
Erg, 106
Ether, 367
Evaporation, 53; effect of temperature on, 168; of solids, 168; effect of air on, 171, 172; cooling effect of, 176; freezing by, 178; effect of air currents on, 178; effect of surface on, 179; and boiling, 184
Expansion, of gases, 136; of liquids, 138; of solids, 139; unequal, of metals, 142; cooling by, 155; on solidifying, 165
Eye, 392; pupil of, 392; nearsighted, 393; farsighted, 393

Fahrenheit, 131
Falling bodies, 72–78
Faraday, 251, 290; portrait of, 290
Fields, magnetic, 219
Films, contractility of, 95; color of, 408
Fire syringe, 155
Fireless cooker, 206
Float valve, 442
Floating dry dock, 438
Floating needle, 100
Flotation, law of, 22
Focal length, of convex lens, 378; of convex mirror, 385, 453
Fog, formation of, 174
Foley, 387
Foot-candle, 376
Force, beneath liquid, 11; definition of, 57; method of measuring, 57; composition of, 59; resultant of, 59; component of, 61, 62; centrifugal, 84; lines of, 218; fields of, 219
Formula for lenses and mirrors, 388
Foucault, 358
Foucault currents, 309
Franklin, 236; portrait of, 230; kite experiment of, 231
Fraunhofer lines, 414
Freezing mixtures, 188
Freezing points, table of, 164; of solutions, 187
Friction, 144 ff.
Frost, formation of, 174
Fundamentals, defined, 341; in pipes, 349, 350
Fuse, electric, 269
Fusion, heat of, 161, 162

Galileo, 72, 73, 128, 132; portrait of, 72
Galvani, 245
Galvanic cell, 245
Galvanometer, 256, 257
Gas engine, 191, 194
Gas heating coil, 213
Gas mask, 103
Gas meter, 46; dials of, 48
Gay-Lussac, law of, 136
Geissler tubes, 427
Gilbert, 225; portrait of, 222
Gliding, principle of, 78–80
Governor, 192
Gram, of mass, 4; of force, 57; of force, variation of, 58
Gramophone, 355

Gravitation, law of, 66
Gravity, variation of, 58, 67; center of, 68
Guericke, Otto von, 31, 41; portrait of, 32
Gun, 354-mm., in action, 73
Gyrocompass, 83, 223

Hail, formation of, 174
Hardness, 92
Harmony, 347
Hay scales, 120
Headlight, automobile, 400
Heat, mechanical equivalent of, 151 ff.; unit of, 152; produced by friction, 153; produced by collision, 154; produced by compression, 154; specific, 158; of fusion, 161; of vaporization, 181; transference of, 203
Heating, by hot air, 211; by hot water, 212; by steam, 213
Heating effects of electric currents, 284, 289
Helium, 45, 435
Helmholtz, 345
Henry, Joseph, portrait of, 246
Henry's law, 104
Hertz, 422, 426; portrait of, 102
Heusler alloys, 216
Hiero, 21
Hirn, 154
Hooke's law, 91
Horse power, 122
Humidity, 175
Huygens, 364, 372; portrait of, 364
Hydraulic elevator, 18
Hydraulic press, 17
Hydraulic ram, 88, 89
Hydrogen thermometer, 132
Hydrometer, 23
Hydrostatic bellows, 437
Hydrostatic paradox, 14
Hygrometry, 173

Ice, manufactured, 201
Ignition, automobile system of, 198, 199
Images, by convex lenses, 378 ff.; size of, 381; virtual, 382; by concave lenses, 382; in plane mirrors, 383; in convex mirrors, 384, 386; in concave mirrors, 384, 387

Imperator, 200
Incandescent lighting, 285
Incidence, angle of, 358
Inclination, 223
Inclined plane, 63, 117
Index of refraction, 371
Induction, magnetic, 216; electrostatic, 228; charging by, 230; of current, 290
Induction coil, 308
Induction motor, 291
Inertia, 83
Insect on water, 100
Insulators, 227
Intensity, of sound, 326; of illumination, 374
Interference, of sound, 333; of light, 365
Ions, 235, 249, 273
Iron, electric, 269
Isoclinic lines, 447
Isogonic lines, 223

Jackscrew, 118
Joule, 106, 122, 151 ff.; portrait of, 122

Kelvin, portrait of, 134
Kilogram, the standard, 4
Kilowatt, 122
Kilowatt hour, 285
Kinetic energy, 123, 126
Kirchhoff, 415

Laminated cores, 310
Lamps, incandescent, 285; arc, 286; Cooper-Hewitt, 288
Lantern, projecting, 391
Leclanché cell, 277
Lenses, 378 ff.; optical center of, 378; principal axis of, 378; principal focus of, 378; formula for, 380; magnifying power of, 395; achromatic, 410
Lenz's law, 291
Level of water, 13
Lever, 110 ff.; compound, 120
Leviathan, 135
Leyden jar, 241
Liberty motor, 191
Light, speed of, 357; reflection of, 358; diffusion of, 359; refraction of, 360; nature of, 364; corpuscular theory of, 364; wave theory of,

364; interference of, 365; wave length of, 367, 403; intensity of, 374; electromagnetic theory of, 426
Lightning, 236
Lightning rods, 236
Lines, of force, 218; isogonic, 223
Liquids, densities of, 9; pressure in, 13; transmission of pressure by, 15; incompressibility of, 33; expansion of, 138
Liter, 3
Local action, 272
Locomotive, 192; *Mallet*, 123; *Rocket*, 123
Loudness of sound, 326

Machines, general law of, 116, 124, 156; efficiencies of, 147
Magdeburg hemispheres, 33
Magnet, natural, 214; laws of the, 215; poles of the, 215; lifting, 247
Magnetism, 214 ff.; nature of, 220; theory of, 221; terrestrial, 222; residual, 301
Magnifying power, of lens, 395; of telescope, 396; of microscope, 397; of opera glass, 398
Malleability, 92
Manometric flames, 343
Marconi, 423; portrait of, 316
Mass, unit of, 4; measurement of, 6
Matter, three states of, 55
Maxwell, 426; portrait of, 102
Mechanical advantage, 109
Mechanical equivalent of heat, 153 ff.
Melting points, table of, 164; effect of pressure on, 166
Meter, standard, 3
Michelson, 357; portrait of, 358
Microphone, 315
Microscope, 397
Mirrors, 383 ff.; convex, 384, 386; concave, 384, 387; formula for, 388
Mixtures, method of, 159
Molecular constitution of matter, 49
Molecular forces, in solids, 90; in liquids, 93
Molecular motions, in gases, 49, 50; in liquids, 53; in solids, 55
Molecular nature of magnetism, 220
Molecular velocities, 52, 129
Moments of force, 111
Momentum defined, 84
Morse, 260; portrait of, 260
Motion, uniformly accelerated, 75; laws of, 76; perpetual, 156
Motor, Liberty, 191; electric-induction, 291; street-car, 302. *See also* Electric motor
Motor rule, 293
Moving pictures, 386

Newton, law of gravitation, 66; laws of motion, 83–87; portrait of, 84; principle of work, 116; corpuscular theory, 364
Niagara, 157
Nichols, E. F., 417
Nodes, in pipes, 334; in strings, 340
Noise and music, 325
Nonconductors, of heat, 205; of electricity, 227
North magnetic pole, 222

Ocean currents, 207
Oersted, 246; portrait of, 246
Ohm, 263; portrait of, 268
Ohm's law, 267
Onnes, Kamerlingh, 135, 178
Opera glass, 398
Optical instruments, 390 ff.
Organ pipes, 353, 354
Oscillatory discharge, 422
Overtones, 341; in pipes, 350

Parabolic reflector, 400
Parachute, 44
Parallel connections, 270, 280
Parallelogram law, 61
Pascal, 15, 16, 30
Pendulum, force moving, 64; laws of, 81; compensated, 141
Periscope, 400
Permeability, 217
Perpetual motion, 156
Perrier, 30
Phonograph, 355
Photometers, 374, 376
Pisa, tower of, 72
Pitch, cause of, 325
Pneumatic inkstand, 33
Points, discharging effect of, 234
Polarization, of galvanic cells, 274; of light, 374
Potential, defined, 237; measurement of, 239, 265; unit of, 277

Power, definition of, 121; horse, 122; electric, 284
Pressure, in liquids, 13; defined, 13; transmission of, by liquids, 15; in air, 27; amount of atmospheric, 29; coefficient of expansion, 133, 136; effect of, on freezing, 166; of saturated vapor, 170; in primary and secondary, 311
Projectile, path of, 78
Pulley, 108 ff.; differential, 119
Pump, air, 33, 41; compression, 41; lift, 42; force, 43

Quality of musical notes, 342
Quebec Bridge, 70

R-34, dirigible airship, 44
Radiation, thermal, 208; invisible, 417 ff.; and temperature, 418; and absorption, 419; electrical, 421
Radioactivity, 431 ff.
Radiometer, 417
Radium, discovery of, 431
Rain, formation of, 174
Rainbow, 411
Ratchet wheel, 146
Rayleigh, portrait of, 358
Rays, infra-red, 417; ultra-violet, 417; cathode, 427; Röntgen, 429; Becquerel, 432; α, β, and γ, 432 ff.
Rectifier, tungar, 314; crystal, 425
Reflection, of sound, 327; of light, 358; angle of, 358; total, 361, 452
Refraction, of light, 360; explanation of, 368; index of, 371
Refrigerator, 163
Regelation, 167
Relay, 260
Resistance, electric, defined, 262; specific, 262; laws of, 262; unit of, 263; internal, 268; measurement of, 269
Resistances, table of, 262
Resonance, acoustical, 328 ff.; electrical, 421
Resonators, 331
Resultant, 59
Retentivity, 217
Retinal fatigue, 407
Right-hand rule, 252, 254
Rise of liquids, in exhausted tubes, 27; in capillary tubes, 97
Roller bearings, 146
Römer, 357
Röntgen, 429; portrait of, 436
Ross, 222
Rotor, generator, 257
Rowland, 155; portrait of, 358
Rubens, 408
Rumford, 151, 374
Rutherford, 432; portrait of, 436

Saturation of vapors, 169; magnetic, 222
Scales, musical, 337; diatonic, 338; even-tempered, 339
Schroeder, 38
Screw, 118
Searchlight, 400
Secondary cells, 281 ff.
Self-induction, 307
Separator, cream, 85
Series connections, 270, 279
Shadows, 362
Shunts, 258, 270
Singing flame, 348
Siphon, explanation of, 40; intermittent, 40
Siren, 337
Sleet, formation of, 174
Snow, formation of, 174
Soap films, 95, 402
Solar spectrum, 414, 415
Sonometers, 339
Sound, sources of, 319; nature of, 319; speed of, 320; musical, 325; intensity of, 326; reflection of, 327
Sound foci, 328
Sound waves, interference of, 333; photographs of, 346, 387
Sounder, 260
Sounding boards, 331
Spark, oscillatory nature of the, 422; in vacuum, 426
Spark length and potential, 240
Spark photography, 422
Speaking tubes, 326
Specific gravity, 9; methods of finding, 22 ff.
Specific heat, defined, 158; measured, 159
Specific heats, table of, 160

Spectra, 411 ff.; continuous, 412; bright-line, 413; pure, 414; solar, 414; X-ray, 437
Spectrum, 403; invisible portions of, 417
Spectrum analysis, 413
Speed, of sound, 320; of light, 357; of light in water, 369; of electric waves, 423 ff.
Spinthariscope, 433
Starting box, 304
Steam engine, 189 ff.
Steam turbine, 199
Steelyards, 115
Stereoscope, 398
Storage cells, 281, 283
Strings, laws of, 339
Sublimation, 168
Submarine, 23, 44
Sun, energy derived from, 157; spectrum of, 414
Surface tension, 95
Sympathetic electrical vibrations, 421
Sympathetic vibrations of sound, 346 ff.

Tank, British, 190
Telegraph, 259 ff.; wireless, 423 ff.
Telephone, 316 ff.; wireless, 424, 431
Telescope, astronomical, 396; Yerkes, 365, 396, 397
Temperature, measurement of, 128; absolute, 134; low, 134
Tenacity, 90
Thermometer, Galileo's, 128; mercury, 129; Fahrenheit, 131; gas, 132–134; alcohol, 132, 134; the dial, 143
Thermos bottle, 209
Thermoscope, 418
Thermostat, 142
Thomson, 428; portrait of, 430
Three-color printing, 408
Torricelli, experiment of, 28
Tower, high-tension, 241
Transformer, 312–314
Transmission, of pressure, 15; electrical, 312; of sound, 321
Transmission, automobile, 196
Transmitter, telephone, 316, 317
Trowbridge, 418
Tungar rectifier, 314
Turbine, water, 149; steam, 199

Units, of length, 2; of area, 2; of volume, 2; of mass, 4; of time, 5; three fundamental, 5; C. G. S., 6; of force, 57, 86; of work, 106; of power, 122, 284; of heat, 152; of magnetic pole, 215; of magnetic field, 219; of current, 251, 257; of resistance, 267; of potential, 277; of light, 375, 376

Vacuum, sound in, 320; spark in, 426
Vaporization, heat of, 181, 182
Velocity, of falling body, 75; of sound, 320; of light, 357
Ventilation, 210, 211
Vibration, forced, 331; of strings, 339; sympathetic, 346 ff.
Vibration numbers, 337
Vision, distance of most distinct, 394; binocular, 398
Visual angle, 394
Volt, 239, 277, 294
Volta, 245; portrait of, 240
Voltmeter, electrostatic, 239; commercial, 265, 266

Watch, balance wheel of, 141; winding mechanism of, 443
Water, density of, 4; city supply of, 19; maximum density of, 138; expansion of, on freezing, 166
Water wheels, 148–150
Watt, 148, 284
Watt, James, 122, 189; portrait of, 122
Watt-hour meter, 304
Wave length, defined, 322; formula for, 323; of yellow light, 367; of other lights, 403
Wave theory of light, 364
Wave train, 322, 424, 425
Waves, condensational, 323; water, 324; longitudinal and transverse, 325; light, are transverse, 371; electric, 422
Weighing by method of substitution, 6
Welsbach mantle, 432
Weston cell, 277
Wet- and dry-bulb hygrometer, 178
Wheel, and axle, 116; gear, 119; worm, 119; water, 148–150

White light, nature of, 403
Wind instruments, 349
Windlass, 120, 443
Winds, 207
Wireless telegraphy, 423 ff.
Wireless telephony, 424, 431
Work, defined, 105; units of, 106; principle of, 116, 125, 156
Wright, Orville, 317; portrait of, 316

X-ray picture of human thorax, 359
X-ray spectra, 430, 437
X rays, 429 ff.

Yale lock, 442
Yard, 2
Yerkes telescope, 365, 396, 397

Zeiss binocular, 399